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TOPICAL DISCUSSION
ON
MAGNETIC ANALYSIS.

MAGNETIC ANALYSIS AS A CRITERION OF THE QUALITY OF STEEL AND STEEL PRODUCTS.

By Charles W. Burrows and Frank P. Fahy.

SUMMARY.

The present paper is intended to contribute to the advancement and the practical application of magnetic analysis from five different viewpoints.

1. *Correlation of Magnetic and Mechanical Data.*—Magnetic analysis requires for its successful practical application the collection of many data for correlating the magnetic and mechanical properties of materials. A considerable amount of data on the magnetic and other physical properties of certain steels is here given.

2. *Possible Magnetic Criteria of Mechanical Performance.*—An effort is made to choose from the many magnetic quantities a limited number which may be used as indicative of the mechanical properties of the material. Obviously the simpler the magnetic data are and the more easily they are determined, the more useful the magnetic test will be.

3. *Magnetic Measurement.*—Several methods of magnetic measurements are described in so far as they differ from the usual well-understood magnetic tests.

4. *Practical Applications.*—Results of magnetic tests on a number of steel products are given to show how such tests may be of assistance in indicating the mechanical properties of a piece of steel or steel instrument. Among the objects examined are steel rails, knife blades, drills, etc.

5. *Future Developments.*—The importance of this presentation lies as much in indicating the possibilities of this method of research and practical testing as in the description of actual accomplishments. The changes in the magnetic properties of materials, resulting from thermal and mechanical treatment, are strikingly significant and give this new method of test promise of considerable commercial importance. With present methods of inspection, it is frequently impossible to differentiate adequately, without destroying the material, between ordinary and exceptional products made of the same stock. It is believed that herein lies one of the most fruitful fields for this method of analysis. Any test method which will facilitate the ready duplication of the best product warrants the most thorough investigation.

From the large mass of more or less isolated data presented in the paper two important generalizations are brought out:

1. The principle that there is a very close relationship between the magnetic and the mechanical characteristics of steel is established on a firm basis.

2. Laboratory tests show that the commercial application of magnetic analysis to shop routine practice is practicable.

Magnetic analysis may be applied to the study of the effects of heat and mechanical treatments and of the changes that occur during or as a result of alternating, repeated or continued stresses. It may be used to detect the presence of flaws in raw material or in the finished product. It may be used, at least in part, as a method for testing high grade steel products such as cutlery, tools, springs, rails, automobile parts, etc.

The general applicability of this method is limited by the two facts: first, that certain shapes are difficult to test; and second, that more data on the correlation of the magnetic and mechanical properties of steel are still required.

MAGNETIC ANALYSIS AS A CRITERION OF THE QUALITY OF STEEL AND STEEL PRODUCTS.[1]

By Charles W. Burrows and Frank P. Fahy.

Magnetic Quantities.

Let us suppose that we have a long hollow cylinder wound uniformly with one or more layers of insulated copper wire. Such a winding is called a solenoid. Suppose also that we have placed within this solenoid, and with its axis parallel to the axis of the solenoid, a coil of small wire wound in a single layer with the terminal leads carefully twisted about each other to avoid loops, and connected to the terminals of a galvanometer of rather long period. If now, we cause an electric current to flow through the winding of the solenoid, there will be a temporary deflection of the galvanometer. On opening the solenoid circuit, the galvanometer will deflect to an equal amount in the opposite direction. If we permit double the original current to flow through the solenoid, the galvanometer will show double the original effect.

If we replace the solenoid by another of twice the number of turns per unit of length and permit a current of the original amount to flow through the windings, the galvanometer will indicate double the previous throw.

It is therefore evident that the solenoid has produced some change in the region occupied by the test coil and that this change is proportional to the product of the number of turns per unit length and the current.

Suppose again, that before we permit the current to flow through the solenoid we insert a long unmagnetized steel wire along the common axis of the test coil and the solenoid. On the make of the solenoid current the galvanometer experiences a much greater deflection than when the steel was not present. On the break the galvanometer gives a reverse deflection, but much smaller than the initial one with the steel in place.

If now we make the current in the reverse direction the galvanometer gives a deflection, which added to that on the break is approximately double that due to the initial make.

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[1] This paper is based upon experimental work conducted by the authors at the U. S. Bureau of Standards.

If instead of breaking the current we reverse it, the galvanometer gives a deflection double that due to the initial make. Since on the reversal of current in the solenoid all conditions are reversed we shall use the corresponding deflection of the galvanometer as a measure of the conditions within the test coil.

If after the initial make and break of the current, the long steel wire is removed from the solenoid, the galvanometer deflects and the steel wire is found to have the following properties:

1. It will, if freely suspended in a horizontal position, tend to assume a direction approximately north and south.

2. If, while it is so suspended, another similarly treated steel wire is brought near it, each end of the suspended steel wire will be repelled by the corresponding end, and attracted by the opposite end of the other wire.

3. The above forces decrease as the distance between the opposing ends increases.

In other words, the steel wire so treated has become a permanent magnet. If a larger current had been made and broken while the steel needle was within it, the galvanometer deflection on removal of the wire and also the force between the two magnets would have been greater. We may therefore use the galvanometer deflection as a measure of the magnetization, or better, the magnetic flux in the steel. It is customary to speak of the magnetic flux per unit cross-section of the steel, and to call the latter quantity the "magnetic induction." Likewise since the magnetization was induced by the current in the solenoid, we may use the galvanometer deflection when no iron is within the solenoid as a measure of the magnetizing force due to the solenoid at the point where the test coil is situated.

If now the magnetized wire is brought near the test coil but not inserted within it, a momentary deflection of the galvanometer occurs. Therefore the magnetized steel itself exerts a magnetizing force similar to that due to the solenoid. Experiment shows that this magnetizing force is due to the presence of the ends of the wire and disappears if the ends of the wire are properly welded together, so as to form a continuous homogeneous ring, and magnetized in a coil of suitable shape.

From the above, it is evident that two quantities are involved in magnetization; the magnetic flux and the magnetizing force.

The relationship between the magnetic flux and the magnetizing force is represented by the curve *OAX* of Fig. 1. For small magnetizing forces the magnetic induction increases almost linearly. As the magnetizing force is increased in magnitude, the rate of increase of induction increases to a maximum. For still larger magnetizing forces, the induction increases, but less and less rapidly.

If, after the induction has reached the value represented by the point *A*, the magnetizing force is gradually decreased, the induction does not decrease in the same manner as it increased, but falls off more slowly. When the magnetizing force has become zero, the induction still has a considerable value, as shown at *B*. The induction is not reduced to zero until the magnetizing force has been reversed and increased to a certain negative value represented by the point *C*. For larger values of the reversed magnetizing force, the induction changes sign, and increases rapidly in magnitude until, at *D*, the same values of induction and magnetizing force exist as existed at

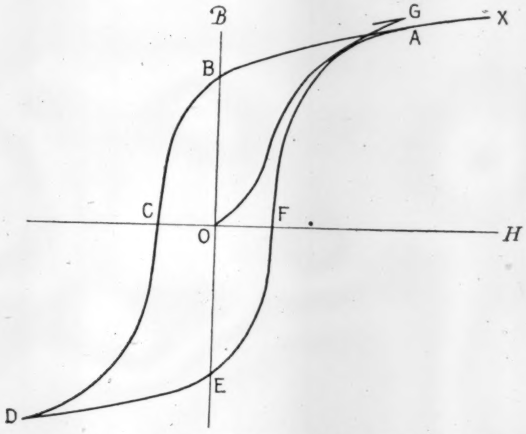

FIG. 1.—Showing the Course of Magnetic Induction when the Magnetizing Force is Carried through a Cycle for the First Time since the Material was Demagnetized.

the point A, only in the opposite direction. On decreasing and then reversing the magnetizing current the induction traces out the path $D\ E\ F\ G$ which is quite similar to the path $A\ B\ C\ D$. However, the complete cycle in magnetizing force does not bring the induction back to its initial value, although the difference is not great. A second cycle of magnetizing force more nearly forms a closed loop. After a certain number of cycles, depending upon the nature of the material and the value of the magnetizing force, the ascending and descending parts of the curve form a closed loop. A different maximum value of the magnetizing force, except for points near saturation, would yield a different loop. This loop is generally called the "hysteresis loop."

Magnetizing Force.—The magnetizing force, or magnetic field intensity, at any point in a magnetic field is defined as numerically equal to the mechanical force acting upon a unit magnetic pole at that point. The unit is called the gauss or the gilbert per centimeter. Within a very long, uniformly wound solenoid of N turns and L centimeters in length, carrying a current of I amperes, the magnetizing force, H, is,

$$H = 0.4\,\pi \frac{NI}{L} = 1.257 \frac{NI}{L}$$

Induction.—The induction B in a bar of iron or steel may be defined in terms of the quantity of electricity which flows through a test coil closely encircling the specimen when the magnetization in the bar is removed, by the formula

$$B = \frac{QR}{AN} 10^8,$$

where Q = total quantity of electricity in coulombs, R = resistance of the test coil circuit in ohms, A = cross-section of specimen in square centimeters, and N = number of turns in test coil. The unit of induction is called the gauss.

Normal Induction.—If a bar of thoroughly demagnetized iron is subjected to a magnetizing force, it experiences a certain induction. This induction will be greater for a sudden application of the magnetizing force than for a slow growth of magnetizing current. If the magnetizing force is repeatedly applied and removed, the values of the induction obtained differ somewhat. If the magnetizing force is reversed, a change of induction approximately twice the preceding values is obtained. For the first few reversals the change of induction is not constant, but becomes so after a number of reversals. One-half this constant value of the change in induction on reversal of the magnetizing force is called the normal induction. The curve of normal induction is formed by plotting the normal induction as ordinate against the magnetizing force as abscissa.

Permeability.—The ratio between the magnetic induction and the magnetizing force is an important magnitude in the study of magnetism. This ratio is called the permeability and is designated by the Greek letter μ. The curve of permeability plotted against magnetizing force, as represented in Fig. 2 shows the characteristics of the permeability. The permeability is not zero when the magnetizing force is zero, but has a definite value which is called the initial permeability, and is denoted by the symbol μ_0.

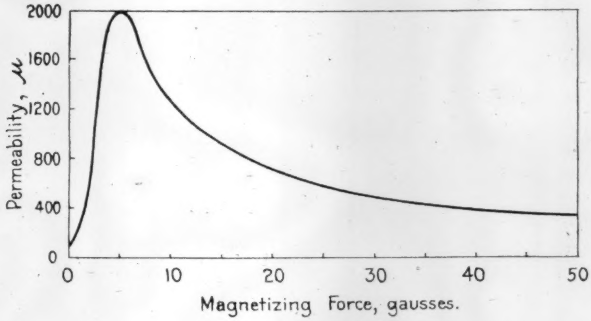

FIG. 2.—Showing the Variation of the Permeability with the Magnetizing Force.

Hysteresis Loop.—A hysteresis loop has several characteristics that are worthy of special note. Since the hysteresis loop is symmetrical about the origin it is sufficient to draw only one-half of it, as shown in Fig. 3. In this figure the part corresponding to increasing induction is called the ascending branch. The other portion is the descending branch. The point corresponding to the highest magnetizing force is called the "tip" of the loop and the corresponding magnetizing force and induction are called the "maximum magnetizing force" and "maximum induction," respectively. These quantities are designated by the symbols H_{max} and B_{max}. The induction that remains when the magnetizing force is reduced to zero is called the "residual induction" and is denoted by the symbol B_r. This residual induction is a fairly constant fraction of the maximum normal induction for all values of the induction below a certain value.

The Coercive Force is the reversed magnetizing force necessary to reduce the induction to zero and is denoted by the symbol H_c. It increases with an increasing magnetizing force up to a certain limiting value. This limiting value ranges from a fraction of a gauss for very pure iron up to 60 or 80 gausses for ordinary hard magnet steel. Certain special steels show even higher values of the coercive force.

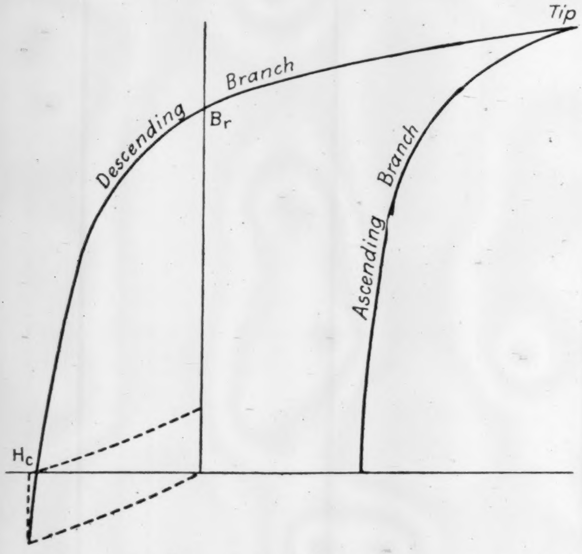

FIG. 3.—Showing the Characteristic Features of a Hysteresis Loop.

MAGNETIC MEASUREMENTS.

The problem of magnetic measurement consists in the determination of simultaneous values of the magnetic induction and the magnetizing force. There is comparatively little difficulty in measuring the magnetic induction. In practically all methods of reasonable degree of accuracy, the total change in the magnetic induction is measured in terms of the impulsive electromotive force induced in a test coil surrounding the specimen, when the direction of the magnetizing force is reversed. This method is simple, accurate and capable of high precision.

The difficulties of measurement center about the determination of the magnetizing force. The magnetizing force has in general a number of components. One component is due to the electric current flowing through the magnetizing coil. This component of the magnetizing force is easily calculated and for certain forms of magnetic circuits the calculation is quite simple. Other components are due to the magnetic poles developed in the various parts of the magnetic circuit due to joints, yokes, non-homogeneities, etc. These components are not susceptible of exact calculation. They can, however, generally be measured, and in some special cases may be neutralized by means of auxiliary magnetizing coils.

Ring Method.—The ring method of magnetic measurement is the simplest. A diagram of its electric circuits is given in Fig. 4. It is described because it illustrates the general principles involved in magnetic measurements and is free from most of the experimental difficulties inherent in the other methods. It also requires the least apparatus and is comparatively free from magnetic difficulties. Its chief objection is in the time-consuming process of winding each test specimen individually.

The test material is in the form of a toroid of convenient dimensions, for example:

Outer diameter	10 cm.
Inner diameter	8 cm.
Cross section	1 sq. cm.

This is wound uniformly with well-insulated fine copper wire (e.g., 100 turns of No. 32). Over this, several layers of coarse wire are wound uniformly (e.g., 4 layers of No. 18 D. C. C.).

Before any observations are taken the specimen must be demagnetized. The usual procedure is as follows: With the switch S on the "measure" side and the galvanometer key K open, adjust the magnetizing current to a high value. Demagnetize by reversing about twice a second for 50 seconds and simultaneously reducing the current to a value below the lowest to be used in the test. After demagnetization the magnetizing current is adjusted to the lowest value desired and reversed several times in order to bring the specimen into a cyclic magnetic condition. The galvanometer key *K* is closed and the deflection of the galvanometer observed. To calibrate the galvanometer throw the switch *S* on the "calibrate" side, reverse the current through the primary of the mutual inductance and note the galvanometer deflection. It may be necessary to adjust the damping and sensitivity resistances of the galvanometer circuit so as to give critical damping at the proper sensitivity.

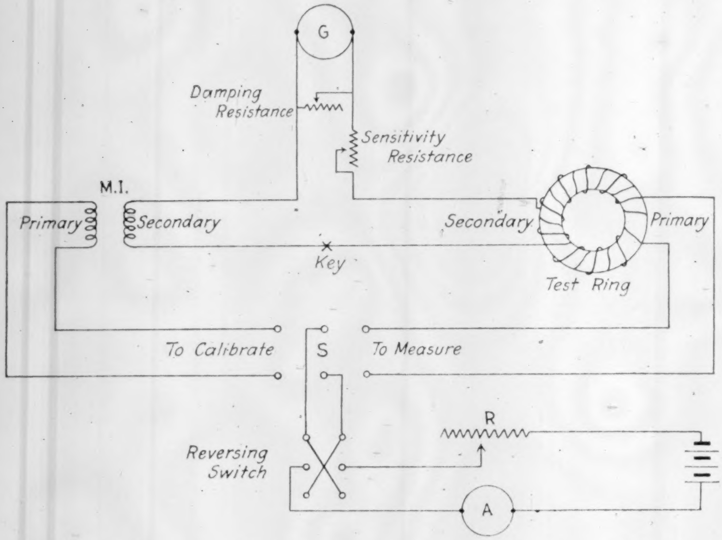
G
Damping Resistance
Sensitivity Resistance
M.I.
Primary
Secondary
Secondary
Primary
Key
Test Ring
To Calibrate
S
To Measure
R
Reversing Switch
A

FIG. 4.—Diagram of Electrical Connections for the Ring Method.

The galvanometer should be of the D'Arsonval type and have a period not less than 10 seconds or greater than 60 seconds. If the period is too short error may be introduced; if it is too long, time is wasted. The damping resistance is connected across the galvanometer terminals and its value adjusted so that the deflection of the galvanometer is aperiodic. The sensitivity of the galvanometer is adjusted to the proper value by means of the sensitivity resistance in series with it.

The mutual inductance should be of such a value that a suitable galvanometer deflection is given with an easily obtained and measured primary current, for example, 0.01 henry.

While the ring method is simple in theory and in manipulation, it is not suited to specimens of other forms. For general use a permeameter which will accommodate specimens of bar form is more convenient.

In the present investigation three types of permeameter have been used. The Burrows[1] permeameter is the standard method. Most of the data presented in this paper have been obtained with the Fahy[2] permeameter. For the determination of the magnetic characteristics of steel rails a special rail permeameter was designed.

Rail Permeameter.—The measurement of the magnetic characteristics of rails could be made by means of a Burrows permeameter of suitable size. However, an instrument of this type suitable for rails would require a length of 3 meters (10 ft.) between yoke ends. The magnetizing solenoids would have to be about 3 meters long and have an inside diameter not less than 20 cm. (8 in.) in order to accommodate the usual sizes of rails. Apparatus of such dimensions would present a number of electrical difficulties. The large magnetizing coils and the great mass of the test specimen would have a large self inductance. The large size of the coil would require a high electromotive force if wire of the same size as used in the smaller apparatus were used. If larger wire is used a correspondingly larger current is required to produce corresponding values of the magnetizing force. In either case the auxiliary electrical apparatus such as storage battery, resistances and switches would require more careful consideration than in the case of the smaller apparatus.

These difficulties are inherent in the testing of such heavy steel specimens. However, they may be considerably reduced by the use of a new form of testing apparatus, called a "rail permeameter," illustrated diagrammatically in Fig. 5. The form shown has been developed after considerable experimentation and is found to be easy of manipulation and also to give good magnetic results.

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[1] *Scientific Paper No. 117,* U. S. Bureau of Standards.

[2] *Scientific Paper No. 306,* U. S. Bureau of Standards.

The magnetic circuit consists of about 2 meters (7 ft.) of the rail under test, a corresponding length of yoke of heavy H-beam parallel to the test piece, and two heavy H-beam pole pieces about 35 cm. (14 in.) long connecting the rail and the yoke. The overhanging portion of the rail and yoke do not introduce any errors into the measurements. In fact these projections are an advantage since they decrease the reluctance of the magnetic path.

The magnetomotive force is applied by means of four coils connected in parallel and arranged as shown.

The measurement of magnetizing force is made by means of a test coil placed near the rail. By one of the fundamental principles of magnetic induction the magnetizing force parallel to the surface of the rail has the same value within the metal and in the air just outside the metal. If therefore a test coil is placed near the surface of the rail with its axis parallel to the length of the rail we have a means of measuring the magnetizing force acting upon the test specimen. The magnetizing force is given by the formula

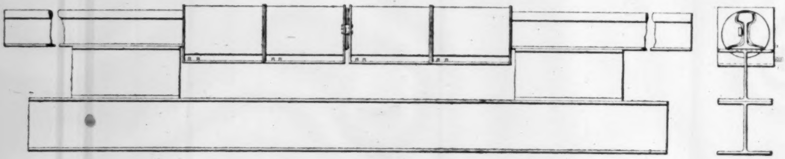

FIG. 5.—Showing the Magnetic Circuit of the Rail Permeameter and the Position of the Magnetizing and Test Coils.

$$H = \frac{K}{A\,N}\,d,$$

where K is the constant of the ballistic galvanometer and is determined as indicated in the ring method, $A\ N$ is the number of area turns, and d is the galvanometer deflection on reversal of the induction in the specimen.

Leakage Measurements.—Changes in the permeability along the length of a test specimen in a uniform magnetic field are evidenced by the leakage of magnetic flux through the air from one part of the bar to another. A bar perfectly uniform in cross-section and material and lying in a uniform field will show no magnetic leakage. A bar with non-uniformities of cross-section or material in a uniform field will show local magnetic poles in the boundary regions between parts of different nature or cross-section. The measurement of magnetic leakage therefore is a delicate test for homogeneity along the length of the specimen. The experimental details depend upon the size and nature of the material to be tested and are described later.

MAGNETIC CHARACTERISTICS OF CERTAIN STEELS.

Heat treatment plays an important role in the shop handling of many steels designed for use under conditions where the steel in its natural or rolled condition has not the physical properties required in the particular service for which it is intended. Heat treatment, as the term is used in this paper, indicates any definite thermal treatment, or procedure, to which the steel may be subjected. More particularly, the term implies a sequence of heating, quenching and drawing operations in which the material is successively heated above a definite critical temperature, quenched, that is, cooled more or less rapidly to harden it, and then reheated to a relatively low temperature and slowly cooled to modify the hardness to the desired degree. The process of reheating followed by slow cooling is termed "drawing."

The writers have investigated the changes in the magnetic characteristics resulting from careful heat treatment operations on several grades of steel in order to observe whether or not these characteristics vary systematically with the treatment to which these materials are subjected. The law of such variations once established for a definite grade of steel would naturally be of great value in determining whether definite thermal processes, laid down as desirable from the results of practical experience, have been correctly carried out.

CARBON STEEL.

Steel having a carbon content of about 1 per cent is used extensively. The magnetic changes produced in this material by heat treatment have been investigated in considerable detail although typical results only are given in this paper. The specimens examined in these experiments are of open-hearth steel and measured $1\frac{3}{16}$ by $\frac{3}{8}$ by 10 in. The magnetic tests were made with the Fahy permeameter. The chemical composition of the steel is indicated by the following analysis:

Carbon	1.04	per cent
Manganese	0.34	"
Phosphorus	0.047	"
Sulfur	0.038	"
Silicon	0.017	"

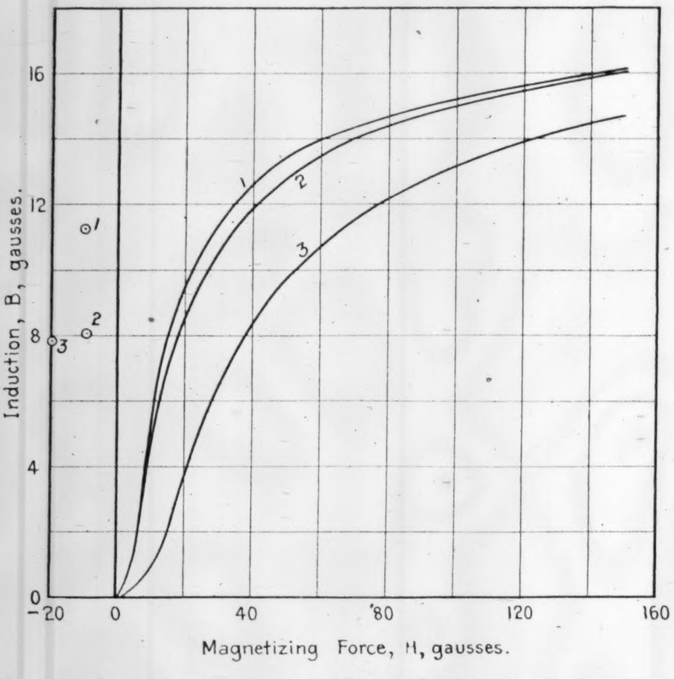

FIG. 6.—Normal Induction and Hysteresis Data for Carbon Steel when (1) annealed; (2) quenched in water from below the critical point and (3) quenched in oil from above the critical point. $H_{max} = 150$.

The critical point, or that temperature above which this steel must be initially heated in order to harden on subsequent rapid cooling, is at 720° C.

In Fig. 6 are plotted normal induction curves for these specimens (1) in the annealed condition, (2) quenched in water from a temperature below the critical point, and (3) quenched in oil from a temperature above the critical point. The residual induction and coercive force corresponding to each curve of normal induction for a maximum magnetizing force of 150 gausses are represented by a point plotted where an ordinate and an abscissa representing the residual induction and coercive force, respectively, would intersect.

The specimen quenched below the critical point was cooled

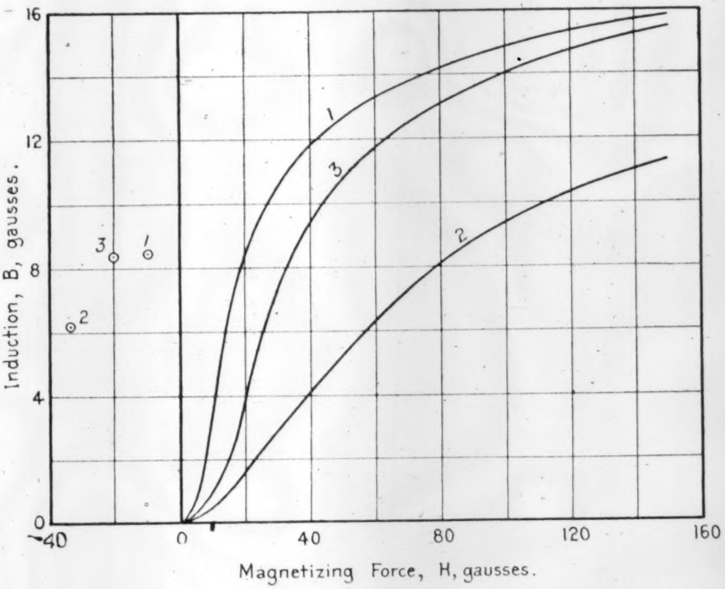

FIG. 7.—Normal Induction and Hysteresis Data for Carbon Steel (1) as received; (2) quenched in water from above the critical point and (3) quenched in oil from above the critical point. $H_{max} = 150$.

in water which was at a temperature of about 2° C. The specimen quenched above the critical point was quenched in oil which was at a temperature of 21° C. The quenching temperatures were respectively 665° and 810° C.

While water quenching generally produces a more intense magnetic hardening than oil quenching, other things being equal, mechanical tests, such as cold bending, show that the specimen which was quenched in the oil has practically no ductility.

Hardness tests determined by the Brinell ball method indicate the former specimen to be very much softer than the latter. The differences are to be ascribed to the temperatures at which quenching was carried out. The oil-quenched specimen has actually been hardened in the usual sense of the term "hardened," while the water-quenched material is practically unchanged, in a mechanical sense, over the annealed condition, although its hardness is slightly increased.

TABLE I.—MAGNETIC AND HARDNESS DATA FOR CARBON STEEL AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force, H, for Magnetic Inductions (B) of								Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	
As received	7.7	10.6	13.9	19.0	27.2	41.5	73.5	159	16 540
Quenched from 800° C.	15.2	20.0	24.9	32.2	43.4	62.5	98.0	174	16 420
Drawn to 100°	14.8	19.7	24.5	31.5	42.2	61.0	96.1	170	16 490
200°	15.0	19.8	24.8	31.3	42.3	60.5	95.6	170	16 490
300°	15.0	19.7	24.8	31.0	41.1	58.5	91.5	160	16 680
400°	14.8	19.8	24.7	31.0	40.8	57.8	90.0	155	16 700
500°	14.8	19.0	23.5	29.0	36.9	50.0	75.7	139	16 940
600°	12.8	16.9	20.3	24.5	30.8	40.8	63.0	130	16 940
700°	8.1	10.8	13.0	16.0	21.0	29.5	54.5	145	16 590
750°	5.5	7.4	9.2	12.0	16.5	26.8	61.0	175	16 260
800°	5.7	8.0	10.0	13.3	18.7	29.8	70.5	197	16 030
950°	6.1	8.8	11.9	16.6	25.3	41.5	85.0	209	15 900

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received	14 850	8 340	9.3	15 850	8 470	9.5	880
Quenched from 800° C.	14 080	8 150	19.5	15 560	8 340	20.0	1 810
Drawn to 100°	14 180	8 200	19.6	15 630	8 400	20.2	1 840
200°	14 180	8 260	19.4	15 630	8 440	20.1	2 060
300°	14 380	8 360	19.6	15 830	8 600	20.2	1 880
400°	14 450	8 450	19.6	15 900	8 670	20.0	1 840
500°	15 000	9 330	19.4	16 240	9 660	19.8	1 510
600°	15 360	10 740	17.4	16 330	11 060	17.8	1 150
700°	15 280	12 180	12.5	16 070	12 440	13.0	840
750°	14 980	11 500	8.8	15 730	11 640	9.2	600
800°	14 680	9 820	8.5	15 480	10 050	8.8	650
950°	14 380	7 920	7.9	15 270	8 060	8.1	800

NOTE.—Quenching was carried out in oil bath at 26° C.

Chemical analysis of steel: C., 1.04; Mn., 0.34; P., 0.047; S., 0.038; Si., 0.017.

In Fig. 7 are plotted the magnetic characteristics of this steel for (1) the rolled condition, that is, the condition in which it is received from the mill and (2) when quenched in water and

(3) in oil. For these quenchings both the water and oil baths were maintained at the same temperature, 26° C., and the temperature from which the specimens were quenched was 800° C., the specimens being heated at the same time and under the same conditions. The marked difference in magnetic characteristics thus obtained is to be noted. While both steels are intensely brittle, showing practically no ductility under a cold bend test, yet the water-quenched specimen is very much the harder, its hardness numeral measured by the Brinell ball method, based upon the load in kilograms required to produce an indentation of 0.1 mm. in depth[1] with a ball 10 mm. in diameter is 4390, while that of the oil-quenched specimen is only 1800.

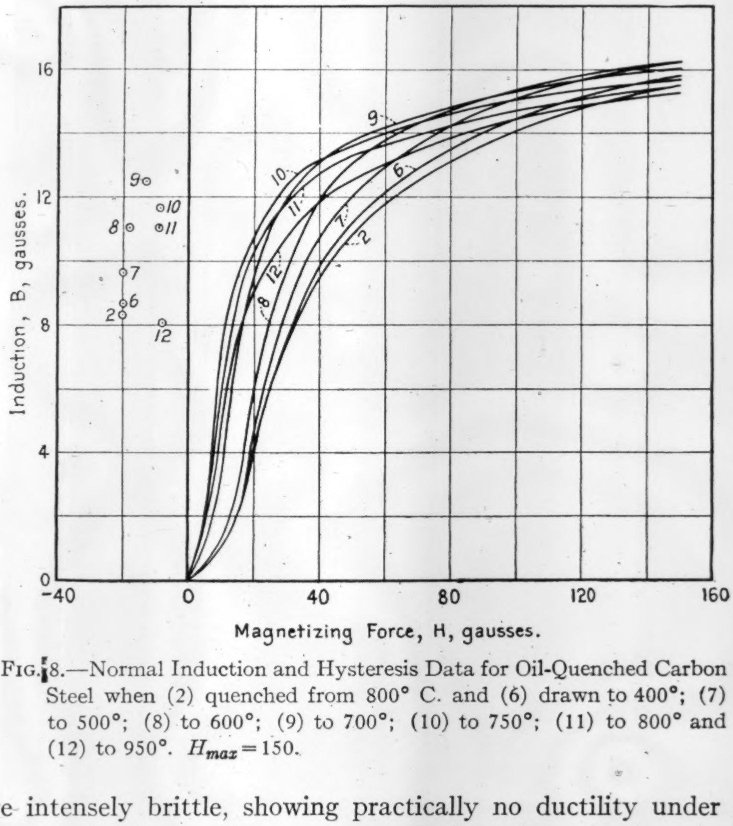

FIG. 8.—Normal Induction and Hysteresis Data for Oil-Quenched Carbon Steel when (2) quenched from 800° C. and (6) drawn to 400°; (7) to 500°; (8) to 600°; (9) to 700°; (10) to 750°; (11) to 800° and (12) to 950°. $H_{max} = 150$.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XI, p. 709–732 (1911).

In order that the magnetic characteristics which accompany a wide range of thermal treatment might be studied rather completely, carbon steel specimens of the above analysis were quenched in oil and water respectively and subsequently reheated to various temperatures both below and above the critical range. Such thermal treatment practically runs the gamut of the various states in which the steel might be commercially utilized. The magnetic examination of the material in each state consisted of the determination of the normal induction

TABLE II.—MAGNETIC AND HARDNESS DATA FOR CARBON STEEL AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force, H, for Magnetic Inductions (B) of								Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	
As received	7.5	10.5	14.5	19.7	28.0	42.5	73.6	159	16 530
Quenched from 800° C.	23.3	39.7	57.4	78.6	111.5	180.	....	...	12 380
Drawn to 100°	22.6	37.0	53.3	72.7	104.5	171.	....	...	12 550
200°	20.2	31.0	42.0	55.0	73.9	111.5	205.	...	13 940
300°	14.4	19.6	22.9	26.2	31.5	40.8	60.5	108	17 580
400°	14.0	19.1	22.2	25.1	29.4	37.2	54.2	97	17 680
500°	15.0	20.1	23.1	26.6	31.5	39.5	57.4	107	17 280
600°	12.0	15.7	18.6	21.6	26.1	33.8	52.0	114	17 050
700°	7.8	10.1	12.1	14.5	18.3	26.2	48.0	135	16 680
750°	5.7	7.7	9.8	12.7	17.0	27.5	59.0	166	16 350
800°	5.7	8.1	10.4	13.7	19.1	31.1	68.0	187	16 150
950°	6.1	9.0	12.5	17.3	25.8	42.0	80.5	196	16 050
Annealed from 800°	8.8	11.9	15.4	19.8	26.6	39.5	71.5	153	16 400

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received	14 850	8 340	9.3	15 850	8 470	9.5	900
Quenched from 800° C.	9 470	5 330	28.7	11 320	6 220	33.4	4 390
Drawn to 100°	9 800	5 710	28.9	11 530	6 500	33.2	4 690
200°	11 520	6 970	28.9	13 050	7 580	31.6	5 160
300°	15 790	10 260	21.4	16 930	10 520	21.8	3 300
400°	16 090	11 280	20.9	17 100	11 590	21.5	2 280
500°	15 810	12 170	22.1	16 750	12 640	22.8	1 540
600°	15 710	12 690	17.7	16 540	13 100	18.2	1 140
700°	15 480	12 600	12.1	16 190	12 760	12.6	820
750°	15 030	11 150	8.9	15 790	11 400	9.2	600
800°	14 780	9 700	8.6	15 590	9 940	8.9	650
950°	14 520	7 600	7.8	15 430	7 700	8.0	790
Annealed from 800°	14 880	9 220	12.0	15 820	9 550	12.2	800

NOTE.—Quenching was carried out in water bath at 26° C.

Specimen annealed from 800° C. represents annealing from the "as-received" condition.

Chemical analysis of steel: C., 1.04; Mn., 0.34; P., 0.047; S., 0.038; Si., 0.017.

up to and including a magnetizing field of 200 gausses, and the maximum induction, residual induction and coercive force corresponding to magnetizing forces of 100 and 150 gausses respectively. Brinell hardness tests were also made by the "depth of indentation" method. These hardness values appear in Tables I and II.

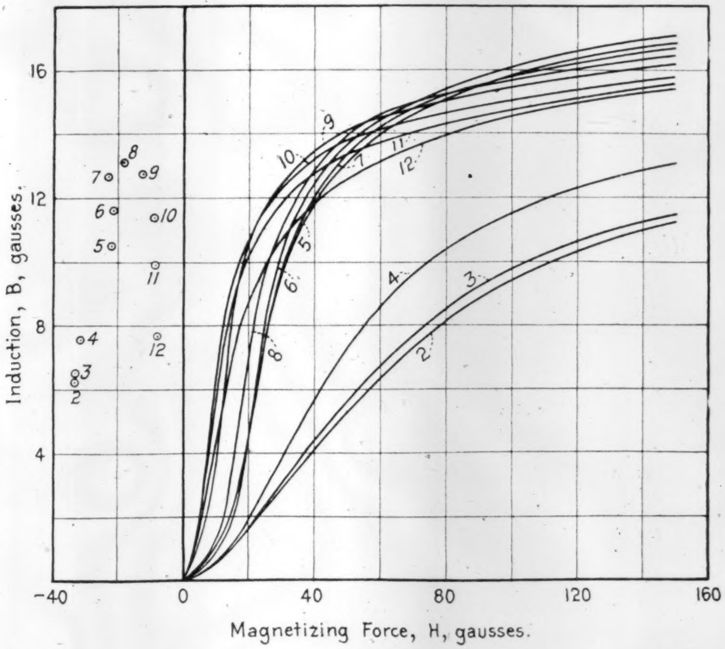

FIG. 9.—Normal Induction and Hysteresis Data for Water-Quenched Carbon Steel when (2) quenched from 800° C. and (3) drawn to 100°; (4) to 200°; (5) to 300°; (6) to 400°; (7) to 500°; (8) to 600°; (9) to 700°; (10) to 750°; (11) to 800° and (12) to 950°. $H_{max} = 150$.

In Table I are recorded the normal induction, hysteresis and hardness data for a carbon-steel specimen in the quenched condition and after drawing to various temperatures. The specimen was quenched from a temperature of 800° C. in an oil bath held at about 26° C. Fig. 8 shows the normal induction curves for a maximum magnetizing force of 150 gausses and the hysteresis values for a maximum magnetizing force of 150 gausses. The curves corresponding to drawing temperatures of 100, 200 and 300° C. are not included, since they are practically similar to those for the steel in the quenched condition. This is also true of the hysteresis values, as may be seen from Table I.

In Table II are recorded the normal induction, hysteresis and hardness data for a carbon-steel specimen of the same analysis in the quenched condition and after drawing to various temperatures. This specimen was quenched from a temperature of 800° C. in a water bath at 26° C. Fig. 9 shows the normal induction curves of the specimen for a maximum magnetizing force of 150 gausses and the corresponding hysteresis values.

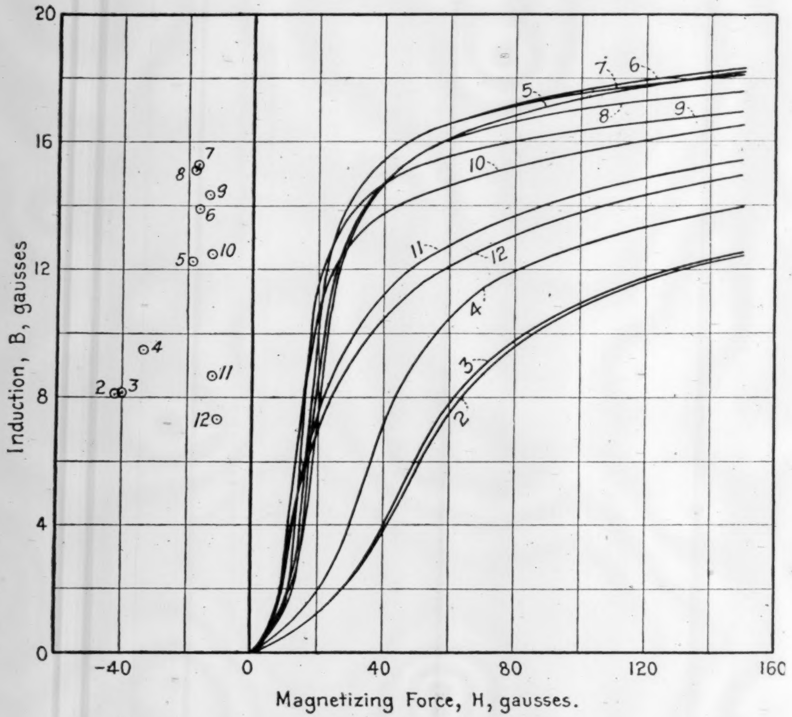

FIG. 10.—Normal Induction and Hysteresis Data for Oil-Quenched Alloy Steel No. 1 when (2) quenched from 800° C. and (3) drawn to 100°; (4) to 200°; (5) to 300°; (6) to 400°; (7) to 500°; (8) to 600°; (9) to 700°; (10) to 750°; (11) to 800° and (12) to 950°. $H_{max} = 150$.

Tables I and II and Figs. 8 and 9 show that the magnetic properties of the oil-quenched carbon steel do not materially change with heat treatment for drawing temperatures up to 400°. On the other hand, water-quenched carbon steel is very susceptible, magnetically, to the influence of low drawing temperatures, showing a considerable change at 100° C., a still greater change at 200°, and at 300° a very large change which results in a maximum permeability comparable with that of the material of the same composition in a very soft state. The water-quenched carbon steel when drawn to 300° C. is, however, very hard in a mechanical sense, despite the increase in permeability.

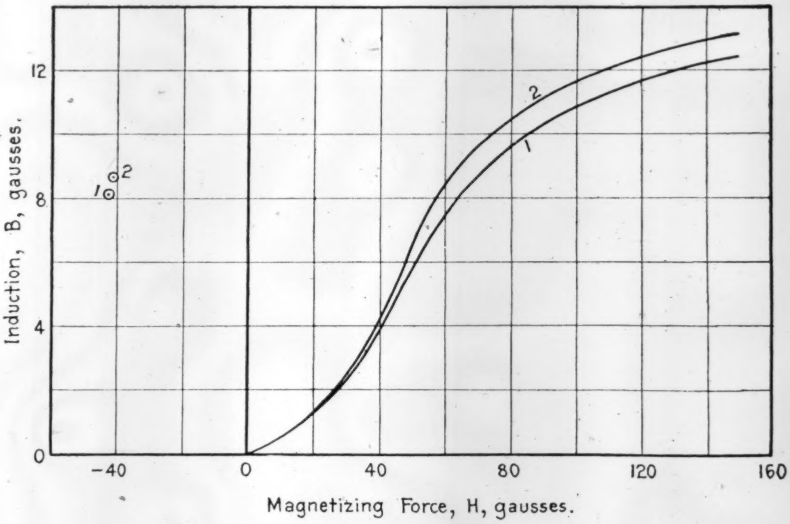

FIG. 11.—Normal Induction and Hysteresis Data for (1) Oil-Quenched and (2) Water-Quenched Alloy Steel No. 1. $H_{max} = 150$.

ALLOY STEELS.

For the determination of the magnetic characteristics resulting from thermal treatment of alloy steel, complete examination was made of two steels of the following composition:

	ALLOY STEEL.	
	No. 1.	No. 2.
Carbon	0.64	0.50
Manganese	0.51	0.74
Phosphorus	0.013	0.013
Sulfur	0.038	0.017
Silicon	0.21	1.94
Nickel	0.63	....
Chromium	0.58	....

Alloy Steel No. 1.—In Fig. 10 are plotted normal induction and hysteresis data for a specimen of alloy No. 1. The specimen was quenched from a temperature of 800° C. in an oil bath at a

TABLE III.—MAGNETIC AND HARDNESS DATA FOR ALLOY STEEL NO. 1 AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force, H, for Magnetic Inductions (B) of									Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	18 000	
As received	10.5	14.0	18.0	23.9	32.5	46.7	73.2	127.0	.....	17 200
Quenched from 800° C.	28.2	41.2	51.5	63.8	85.3	131.5	....	.....	.....	13 330
Drawn to 100°	27.6	40.1	50.2	62.3	83.5	131.5	....	.....	.....	13 370
200°	21.0	30.1	36.5	43.5	55.6	80.4	150.0	.....	.....	14.690
300°	12.0	16.8	18.4	20.3	22.6	26.5	35.2	58.6	132.5	18 740
400°	11.7	15.0	16.7	18.1	20.0	22.5	28.9	46.6	122.0	18 790
500°	12.0	15.2	16.9	18.2	20.0	22.5	28.7	47.6	135.0	18 610
600°	13.5	16.8	18.0	20.0	21.9	25.5	33.0	59.0	195.0	18 050
700°	11.5	13.5	14.9	16.2	17.9	21.5	31.9	77.3	.....	17 390
750°	9.1	11.2	13.1	15.2	19.2	25.5	44.0	114.0	.....	17 000
800°	9.7	12.7	16.4	22.0	30.5	47.6	87.0	187.0	.....	16 160
950°	8.8	12.5	17.4	24.7	36.2	58.8	108.0	.....	.....	15 700

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received	15 200	8 250	13.5	16 500	8 430	13.8	1 150
Quenched from 800° C.	10 830	7 190	38.6	12 440	8 090	42.4	8 300
Drawn to 100°	10 890	7 320	37.5	12 460	8 140	40.2	5 260
200°	12 790	8 920	32.0	14 000	9 500	33.6	4 160
300°	17 390	12 200	18.3	18 240	12 260	18.7	2 920
400°	17 640	13 750	16.6	18 320	13 900	16.7	2 280
500°	17 510	14 990	16.7	18 170	15 250	16.9	1 660
600°	16 970	14 880	18.0	17 620	15 110	18.0	1 330
700°	16 320	14 150	13 3	16 980	14 340	13.2	940
750°	15 740	12 300	11.9	16 530	12 500	12.4	740
800°	14 390	8 500	12.2	15 440	8 680	12.4	800
950°	13 790	7 140	10.8	14 970	7 310	11.0	....

NOTE.—Specimen No. B 16. Quenching was carried out in oil bath at 30° C.
Chemical analysis of steel: C., 0.64; Mn., 0.51; P., 0.013; S., 0.038; Si., 0.21; Ni., 0.63; Cr., 0.58.

temperature of 30° C. The critical point for this steel is 740° C. In Table III are recorded the normal induction, hysteresis, and hardness data for this specimen.

In Table IV are given similar data for a specimen which was quenched from a temperature of 800° C. in a water bath at a temperature of 30° C. The complete normal induction and hysteresis data for this specimen have not been plotted. The data agree, however, in most of the essential details with those for the oil-quenched material of the same chemical composition,

TABLE IV.—MAGNETIC AND HARDNESS DATA FOR ALLOY STEEL NO. 1 AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force H, for Magnetic Inductions (B) of									Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	18 000	
As received	11.0	14.8	18.8	24.5	33.3	47.0	72.0	125.0	.....	17 350
Quenched from 800° C.	27.0	38.9	47.7	57.5	73.5	108.0	195.0	.....	.....	14 080
Drawn to 100°	25.0	36.7	45.3	54.8	70.0	104.0	187.0	.....	.....	14 200
200°	19.5	31.3	33.9	40.1	49.4	68.5	118.0	.....	.....	15 350
300°	12.0	16.1	18.4	20.0	22.0	26.2	35.7	60.0	135.0	18 700
400°	11.8	15.2	17.0	18.6	20.7	23.5	29.9	49.0	124.0	18 700
500°	12.0	15.4	17.8	18.6	20.7	23.5	29.9	49.0	134.0	18 580
600°	13.0	16.2	18.2	20.0	22.0	25.7	33.6	60.0	196.0	18 040
700°	11.3	13.5	14.9	16.3	18.2	21.8	32.0	80.0	.....	17 410
750°	9.0	11.4	13.3	15.8	19.5	26.4	44.5	111.0	.....	17 080
800°	9.4	12.8	16.5	22.1	30.7	47.0	85.0	181.0	.....	16 240
950°	8.4	12.4	17.0	24.2	35.5	57.1	101.6	.....	.....	15 860
Annealed from 750°	11.0	14.1	17.0	20.8	27.0	38.2	62.0	131.0	.....	......

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received	15 260	8 180	14.0	16 570	8 370	14.4	....
Quenched from 800° C.	11 660	7 840	38.8	13 200	8 630	41.0	7 100
Drawn to 100°	11 870	8 130	36.8	13 330	8 870	38.8	7 400
200°	13 500	9 540	30.6	14 620	9 980	32.1	4 890
300°	17 380	12 100	18.0	18 200	12 160	18.4	3 010
400°	17 600	13 500	17.0	18 310	13 630	17.2	2 430
500°	17 490	14 870	16.7	18 150	15 080	17.0	1 650
600°	16 970	14 810	17.6	17 620	15 000	17.6	1 230
700°	16 330	14 040	13.2	16 980	14 240	13.4	990
750°	15 800	12 200	12.0	16 560	12 320	11.9	720
800°	14 470	8 450	12.2	15 540	8 640	12.5	850
950°	13 950	7 030	10.6	15 110	7 190	11.0	....
Annealed from 750°	15 380	9 930	13.5	16 350	10 080	14.0	780

NOTE.—Quenching was carried out in water bath at 30° C.

Specimen annealed from 750° C. represents annealing from the "as-received" condition.

Chemical analysis of steel: C., 0.64; Mn., 0.51; P., 0.013; S., 0.038; Si., 0.21; Ni., 0.63; Cr., 0.58.

except for drawing temperatures below 400° C., where characteristic differences are noted.

In Fig. 11 are plotted the normal induction and hysteresis data for specimens quenched in oil and in water, respectively. The permeability and residual induction are lower and the coercive force higher for the oil-quenched than for the water-quenched material. This is not characteristic of carbon steels but is found to be the case for several alloy steels. Reference to Tables III and IV shows that under oil quenching the material is considerably softer mechanically than under water quenching. In the case of the carbon steels when quenched in water and oil respectively, the greater hardness is associated with the higher coercive force and this higher coercive force occurs under water quenching.

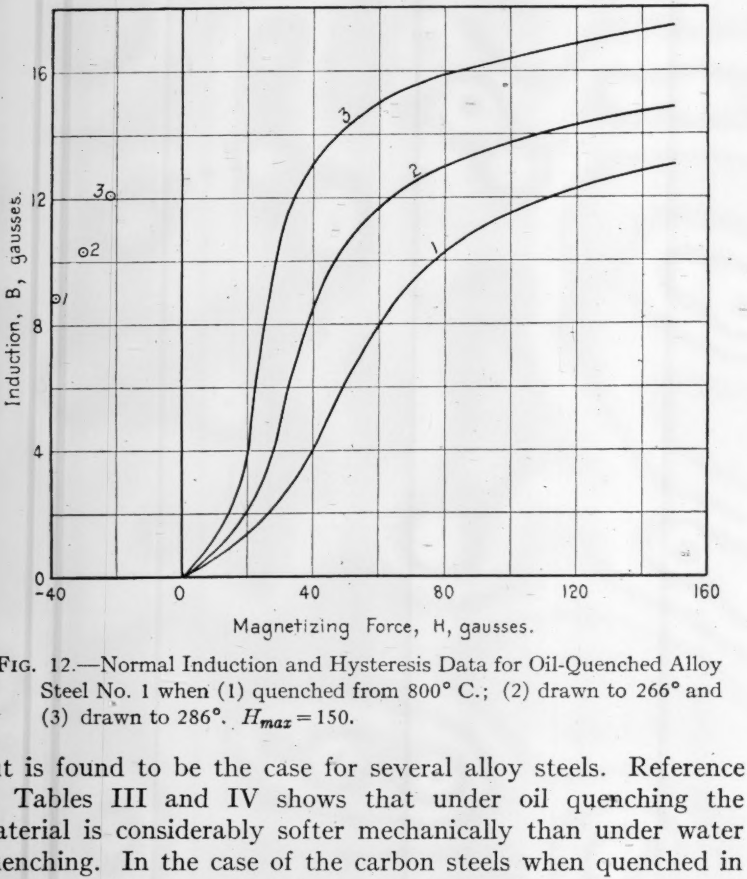

FIG. 12.—Normal Induction and Hysteresis Data for Oil-Quenched Alloy Steel No. 1 when (1) quenched from 800° C.; (2) drawn to 266° and (3) drawn to 286°. $H_{max} = 150$.

It will be noted from Tables III and IV that alloy steel No. 1 when quenched either in water or in oil shows for the same drawing temperatures the corresponding large increase in induction and the decrease in coercive force which is observed in drawing water-quenched carbon steel between 200 and 300° C. In Fig. 12 are plotted normal induction and hysteresis data for oil-quenched material which has been quenched and drawn to 266 and 286° C. Comparing these curves with that plotted in Fig. 9 for a drawing temperature of 200° C. it would appear that the greater part of the change is confined to narrow limits of temperature.

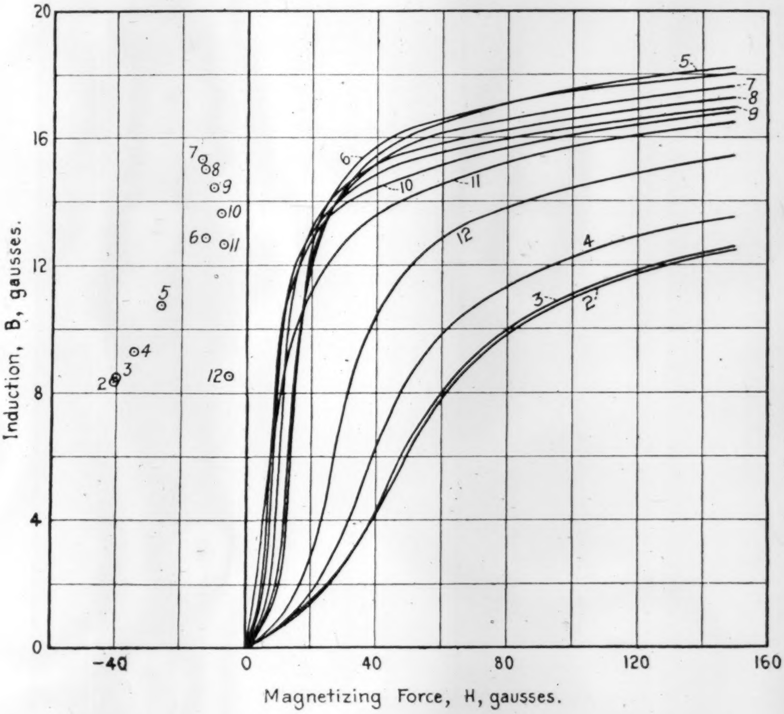

FIG. 13.—Normal Induction and Hysteresis Data for Oil-Quenched Alloy Steel No. 2 when (2) quenched from 955° C. and (3) drawn to 100°; (4) to 200°; (5) to 300°; (6) to 400°; (7) to 500°; (8) to 600°; (9) to 700°; (10) to 750°; (11) to 800° and (12) to 950°. $H_{max} = 150$.

Alloy Steel No. 2.—In Fig. 13 are plotted normal induction and hysteresis data for a specimen of alloy steel No. 2. The quenching for this specimen was carried out from a temperature of 955° C. in an oil bath at 15° C. This grade of steel is manufactured as material suitable for permanent magnets and the manufacturer's recommendation as to the most satisfactory quenching temperature to obtain the maximum hardening effect was followed.

TABLE V.—MAGNETIC AND HARDNESS DATA FOR ALLOY STEEL NO. 2 AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force, H, for Magnetic Inductions (B) of									Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	18 000	
As received..........	5.6	7.8	10.3	13.8	19.2	28.7	48.0	98.2	.....	......
Quenched from 955° C.	25.4	38.5	49.0	61.2	82.3	138.5	....	....	.....	......
Drawn to 100°..	25.4	38.0	47.5	59.6	80.4	125.0	....	....	.....	13 450
200°..	21.8	31.8	38.5	46.6	60.6	93.0	176.0	....	.....	14 320
300°..	16.5	23.1	27.0	31.0	38.2	50.7	86.0	197.	.....	16 030
400°..	9.1	11.8	13.4	14.7	16.1	19.8	27.3	49.3	129.	18 710
500°..	10.5	12.5	14.0	15.3	16.7	19.3	25.1	44.7	144.	18 420
600°..	10.0	12.2	13.4	14.7	16.4	19.5	27.3	56.0	197.	18 030
700°..	7.5	9.1	10.1	11.3	13.0	16.0	25.5	65.4	.....	17 700
750°..	5.4	7.0	8.1	9.3	11.1	15.0	28.0	82.0	.....	17 500
800°..	4.8	6.1	7.7	9.2	11.5	16.0	30.4	93.0	.....	17 310
950°..	3.3	5.5	7.9	10.8	15.5	24.5	45.0	113.0	.....	17 150
Annealed from 830°..	5.6	7.8	10.2	12.4	15.5	21.0	36.6	135.0	.....	......

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received............	16 050	9 480	8.9	16 990	9 540	9.2	960
Quenched from 800° C..	10 980	7 530	37.7	12 530	8 370	41.1	2 970
Drawn to 100°....	11 040	7 670	37.0	12 600	8 470	40.6	3 450
200°....	12 300	8 710	33.5	13 560	9 280	35.2	3 560
300°....	14 410	10 420	26.2	15 430	10 740	26.4	3 050
400°....	17 530	12 740	12.3	18 260	12 820	12.7	2 430
500°....	17 470	15 170	13.6	18 040	15 280	13.8	1 530
600°....	17 000	14 880	12.9	17 630	15 010	13.1	1 360
700°....	16 630	14 350	9.9	17 260	14 420	10.2	990
750°....	16 360	13 470	8.4	17 000	13 620	8.2	820
800°....	16 090	12 500	7.2	16 840	12 640	7.4	860
950°....	15 760	8 290	5.8	16 560	8 500	6.0	890
Annealed from 830°....	16 300	11 710	9.0	17 100	11 800	9.2	950

NOTE.—Quenching was carried out in oil bath at 15° C.

Specimen annealed from 830° C. represents annealing from the "as-received" condition.

Chemical analysis of steel: C., 0.50; Mn., 0.74; P., 0.013; S., 0.017; Si., 1.94.

Here, as in the case of alloy steel No. 1, there are differences to be observed in the magnetic characteristics of the steels, in the quenched condition and under low drawing temperatures, according to whether quenching was performed in oil or water.

TABLE VI.—MAGNETIC AND HARDNESS DATA FOR ALLOY STEEL NO. 2 AFTER VARIOUS HEAT TREATMENTS.

NORMAL INDUCTION.

Condition.	Magnetizing Force, H, for Magnetic Inductions (B) of									Induction, B, for $H=200$.
	2000	4000	6000	8000	10 000	12 000	14 000	16 000	18 000	
As received	6.5	9.0	11.8	15.0	19.8	28.8	48.0	97.5	.....	......
Quenched from 955° C.	22.2	31.0	36.4	42.0	50.2	65.8	106.	.....	.....	......
Drawn to 100°	23.0	32.0	37.7	43.5	52.0	68.1	108.	.....	.....	15 740
200°	19.2	25.7	30.2	34.5	40.5	51.4	79.3	161.	.....	16 500
300°	14.6	19.6	22.5	25.0	28.8	34.4	49.1	95.0	.....	17 600
400°	9.2	12.0	13.2	14.5	15.8	18.6	25.9	47.0	121.	18 830
500°	10.7	13.1	14.6	16.0	17.1	19.8	25.4	43.0	135.	18 550
600°	10.7	12.5	13.8	15.0	16.8	18.9	26.2	53.5	189.	18 080
700°	8.3	9.9	10.8	11.5	13.2	16.0	24.8	63.0	.....	17 800
750°	5.8	7.4	8.0	9.2	11.2	15.0	26.2	78.0	.....	17 600
800°	4.9	6.7	7.8	9.2	11.8	16.1	30.7	91.0	.....	17 390
950°	3.6	5.7	8.1	11.2	15.8	24.7	45.8	110.0	.....	17 180

HYSTERESIS. HARDNESS.

Condition.	For $H=100$.			For $H=150$.			Brinell Hardness, kg. per 0.1 mm. indentation.
	B_{max}	B_r	H_c	B_{max}	B_r	H_c	
As received	16 080	9 160	10.0	17 000	9 250	10.4	960
Quenched from 955° C.	13 800	10 050	35.2	15 090	10 450	36.8	4 150
Drawn to 100°	13 710	9 900	34.0	15 020	10 420	35.2	4 990
200°	14 740	10 850	29.1	15 840	11 200	29.5	3 590
300°	16 110	11 960	22.8	17 040	12 120	23.0	3 190
400°	17 670	12 980	12.6	18 390	13 050	12.8	2 480
500°	17 570	15 280	14.5	18 140	15 440	14.8	1 690
600°	17 060	14 930	13.8	17 670	15 070	13.9	1 280
700°	16 690	14 400	10.3	17 340	14 560	10.6	980
750°	16 420	13 630	8.3	17 140	13 780	8.5	830
800°	16 140	12 450	7.3	16 860	12 620	7.5	780
950°	15 790	8 160	6.0	16 590	8 390	6.3	860

NOTE.—Quenching was carried out in water bath at 15° C.

Chemical analysis of steel: C., 0.50; Mn., 0.74; P., 0.013; S., 0.017; Si., 1.94.

The differences apparently persist up to higher drawing temperatures than in the case of alloy steel No. 1, as may be seen from Tables V and VI. This may be the result of the large differences to be observed in the respective quenched conditions, as shown in Fig. 14.

MISCELLANEOUS STEELS.

In addition to the steels described above, observations have been made of the magnetic characteristics which result from thermal treatment of steels of different composition. Among these may be mentioned a spring steel which exhibits more or less similar properties to alloy steels Nos. 1 and 2. The chemical composition of this steel, referred to as alloy No. 3, is as follows:

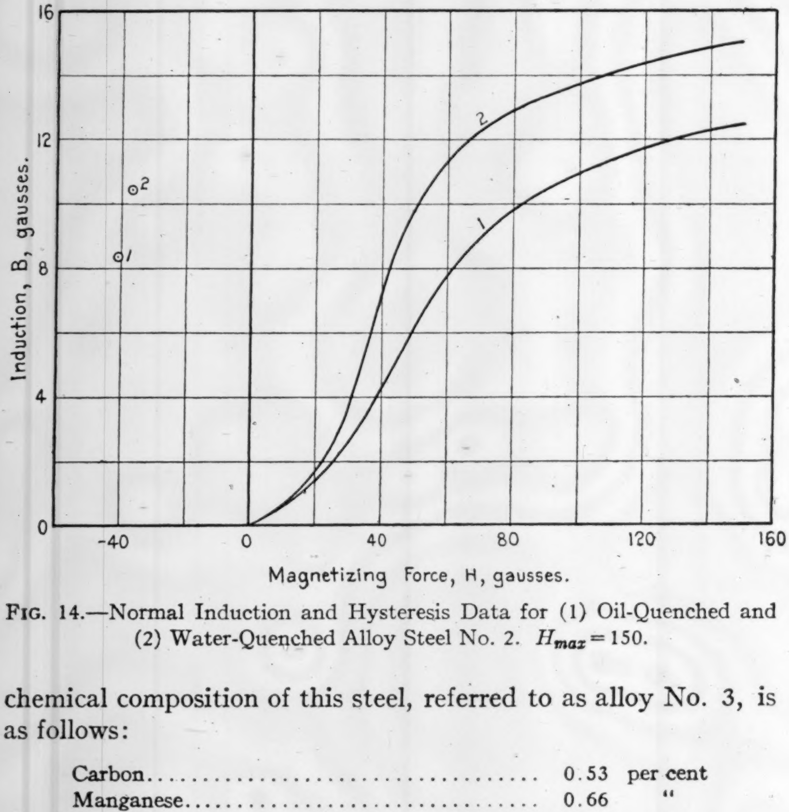

FIG. 14.—Normal Induction and Hysteresis Data for (1) Oil-Quenched and (2) Water-Quenched Alloy Steel No. 2. $H_{max} = 150$.

Carbon	0.53	per cent
Manganese	0.66	"
Phosphorus	0.069	"
Sulfur	0.045	"
Silicon	1.277	"
Nickel	0.175	"

In Fig. 15 are plotted the normal induction data for this steel when annealed, oil-quenched, and quenched and drawn.

The large increase of permeability at high magnetizing forces over that of the annealed and relatively much softer material is to be noted. The steepness of the induction curve, that is, the large increase in induction corresponding to a small change in the magnetizing force, will be referred to later in discussing uniformity.

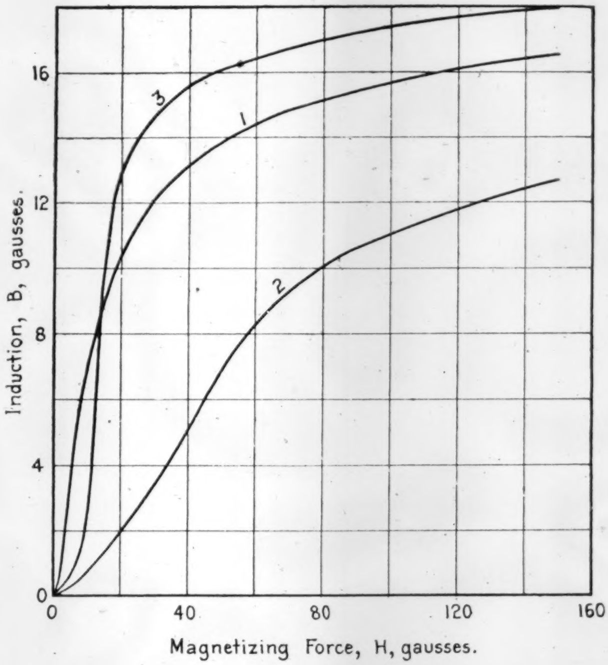

FIG. 15.—Normal Induction Curves for Alloy Steel No. 3 when (1) annealed; (2) quenched in oil at 871° C. and (3) drawn to 482°.

In Fig. 16 are plotted the normal induction curves for alloy steel No. 3 when quenched (1) in water and (2) in oil. The crossing of the induction curves which is noted here apparently does not take place in the case of alloy steels Nos. 1 and 2. It is of course possible that if observation of inductions at extremely low values of magnetizing force had been made in the case of the other alloy steels such crossing would have been noted.

In Fig. 17 are plotted normal induction data for a rail steel of the following analysis:

Carbon	0.82	per cent
Manganese	0.97	"
Phosphorus	0.055	"
Sulfur	0.032	"
Silicon	0.202	"

The curves denote the material (1) as received; (2) slowly annealed from 806° C.; (3) quenched in oil from 820°; and (4) drawn to 700°, after quenching. The numerical increase of Brinell hardness resulting from the oil quenching of this steel was not expressed in the same units as in the case of the material previously described and therefore no direct comparison may be made. But this increase of hardness and the decrease in permeability resulting from the quenching operation is far greater than was to be expected solely from its carbon content which is

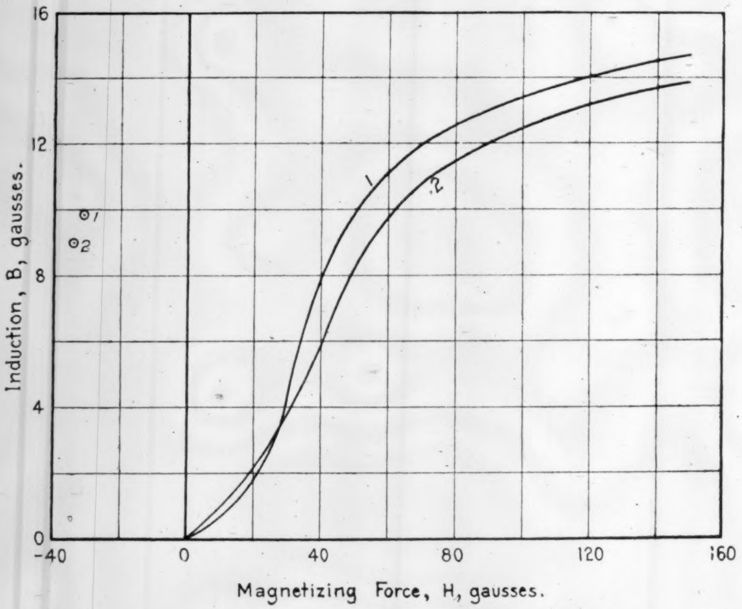

Fig. 16.—Normal Induction Curves for Alloy Steel No. 3 when (1) water-quenched and (2) oil-quenched.

below that of a 1 per cent carbon steel. It is believed that the manganese content may be the influencing factor.

In order to compare the magnetic behavior of this steel under quenching with one closely similar, yet differing in amount of manganese, a selection was made of a steel of the following composition:

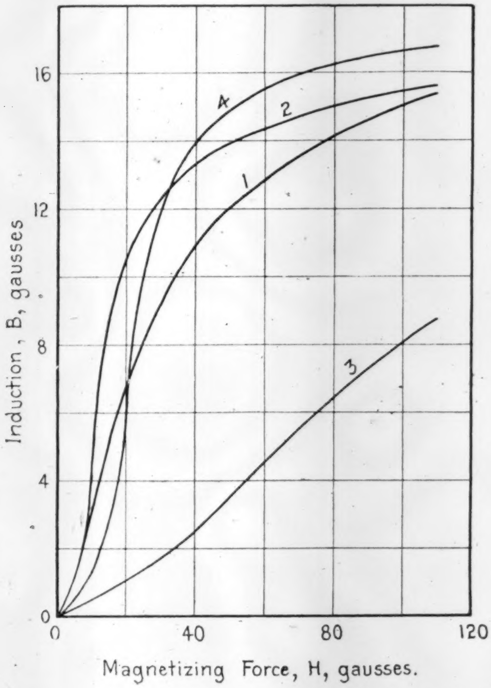

FIG. 17.—Normal Induction Curves for Rail Steel (1) as received; (2) annealed from 806° C.; (3) quenched in oil at 820°; and (4) drawn to 700°.

Carbon	0.90	per cent
Manganese	0.41	"
Phosphorus	0.041	"
Sulfur	0.037	"
Silicon	0.42	"

In Fig. 18 are plotted normal induction curves of these two steels when the one having a carbon content of 0.82 per cent and manganese of 0.97 per cent is (1) annealed and (2) quenched in oil and that having a carbon content of 0.90 per cent and manganese of 0.41 per cent is (3) annealed and (4) quenched in oil. The increase of hardness over the annealed condition as the result of oil quenching in the case of the steel having the high manganese content is practically equivalent to what we find in the case of the low manganese steel under water quenching.

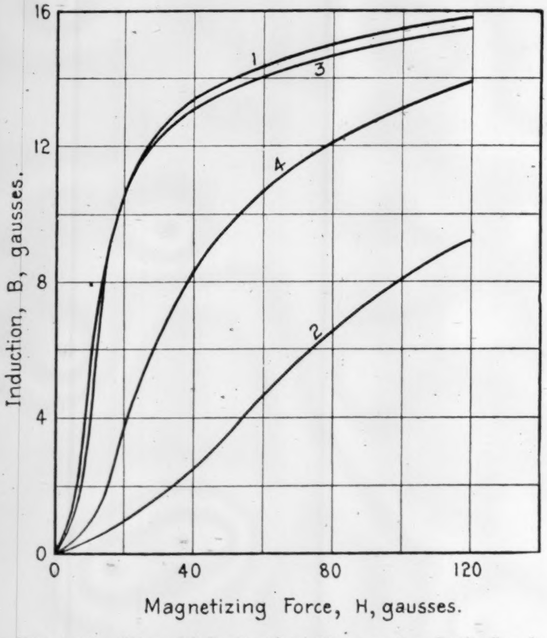

FIG. 18.—Normal Induction Curves for Rail Steel ($C=0.82$, $Mn=0.97$) when (1) annealed and (2) quenched in oil from 820° C.; and for Carbon Steel ($C=0.90$, $Mn=0.41$) when (3) annealed and (4) quenched in oil from 810°.

The silicon content in the lower manganese steel is higher than that of the higher manganese steel and it may therefore be assumed that the manganese alone promotes the hardening effect in quenching. As will be observed from Fig. 18, the decrease in permeability due to quenching in the case of the higher manganese steel is quite great.

The magnetic characteristics of material, and especially the variation in such characteristics over a given section, where the material has been subjected to that heat treatment which is incidental to rolling operations only, presents much interest.

In Fig. 19 are plotted normal induction and hysteresis data for steel cut from similar portions of two rails of the following analyses:

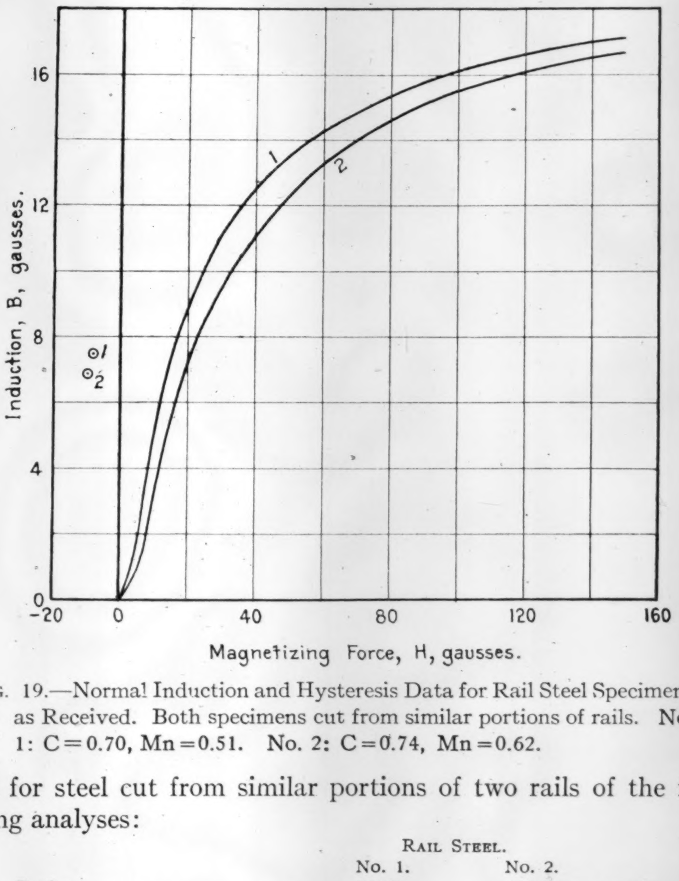

FIG. 19.—Normal Induction and Hysteresis Data for Rail Steel Specimens as Received. Both specimens cut from similar portions of rails. No. 1: C = 0.70, Mn = 0.51. No. 2: C = 0.74, Mn = 0.62.

	RAIL STEEL.		
	No. 1.	No. 2.	
Carbon	0.70	0.74	per cent
Manganese	0.51	0.62	"
Phosphorus	0.045	0.039	"
Sulfur	0.046	0.021	"
Silicon	0.165	0.165	"

It will be noted that the steel having the higher carbon and manganese has lower permeability and residual induction and higher coercive force than the other.

CORRELATION OF MAGNETIC AND OTHER PHYSICAL PROPERTIES.

The shape of the normal induction curve is influenced largely by the nature of the elementary particles, considered as magnets, and their spacing and grouping. When, in the process of magnetization, there is a high degree of uniformity of action of such elemental particles as indicated by a large increase of induction for small increments of magnetizing force, we may assume that such particles are to a considerable degree under similar constraint.

Quenched and undrawn steel is not characterized by such abrupt changes in magnetization as are to be found in steel after drawing. Since steel in the quenched condition is undoubtedly in a highly strained condition, we may consider that, other things being equal, the characteristics of the curve in the second stage of magnetization indicate largely the strain conditions present. The stresses which produce such strains are necessarily of opposite sign, since they must vanish across the section and their relative intensities evidently play an important part in determining the magnetic characteristics. These stresses arise when the intermolecular stresses, or the forces existing between the elemental particles, vary throughout the mass of the material. Under such conditions one portion of the material exerts a force upon another portion and the condition known as internal strain arises.

The magnetic manifestations of such internal strains appear to consist in a lowering of the residual induction with a consequent increase of the evanescent induction. As the quenched material is drawn to successively increasing temperatures, the residual induction at first increases and the evanescent induction decreases. Coincident with such changes, the shape of the normal induction curve is modified in such a manner as to indicate increasing homogeneity.

Review of the hysteresis data in Tables I to VI shows that with certain exceptions, which may be highly significant, the coercive force steadily decreases when the quenched material is reheated up to the critical temperature. Within this same range and up to a point near the critical temperature the residual induction increases. Judging from the mechanical test results of such materials, the desirable reheating temperature when the carbon steel and alloy steel No. 1 is intended for use in spring construction, appears to be 500° C. for the former and 600° C. for the latter. It is at these temperatures that marked changes in residual induction and coercive force occur, one or the other showing a sharp change toward an increasing value.

The changes in the magnetic characteristics are not entirely consistent with the Brinell hardness values obtained. This inconsistency may be explained to some extent by the fact that the hardness test is strongly influenced by the condition of the exterior region of the steel while the values obtained in a magnetic test represent the integral value throughout the mass. However, just as it is shown in these tables that the Brinell hardness may increase upon reheating, so it is entirely possible that changes occur, due to readjustment of stresses, which may bring about an increase in some one of the many forms of hardness which is not expressed by the resistance which the material offers to indentation. Brinell hardness is a measure of the resistance which permanently deformed material offers to further deformation. The magnetic characteristics are those of material not mechanically deformed and a definite relation is not necessarily to be expected.

Possible Magnetic Criteria.—The magnetic characteristics have been correlated rather roughly with chemical and mechanical properties of certain steels. For instance, we know that with increasing carbon content up to a certain limit steel shows an increase in hardness and in tensile strength, and a decrease in ductility. Correspondingly an increase in carbon content shows characteristic changes in the magnetic properties. The permeability and the saturation value decrease with increasing carbon content while the coercive force and hysteresis increase. An increase in the rate of cooling from above the critical temperature has approximately the same effect on the mechanical and magnetic properties as does an increase in carbon content. When, however, we attempt a numerical correlation between a specific pair of magnetic and mechanical characteristics, inconsistencies usually begin to appear as soon as the range in chemical content and heat treatment of the materials compared becomes great. Some magnetic characteristics are more consistent criteria of the general physical properties than are others.

For instance, the coercive force is a better criterion of mechanical hardness than is the permeability. In the attempt to correlate the magnetic and mechanical properties, it is desirable to consider all the magnetic characteristics which may be of assistance. In addition to those already mentioned we may combine in various ways two or more of those given above.

If the chemical content is constant and the only variable is the temperature of quenching, there is no difficulty in finding some one of the magnetic characteristics which will give a smooth curve when plotted against the temperature of quenching. Similarly smooth curves may be obtained for materials of any other one variable. The problem increases in difficulty as the number of variables increases. In any case the problem is to determine the criterion or criteria which will best and in the simplest manner indicate the desired mechanical characteristics.

APPLICATION OF INDUCTION TEST.

Cutlery.—An important practical application of magnetic analysis is the examination of knife blades and other similar cutting tools. A good knife blade must be straight and have a surface free from irregularities. The blade must be free from cracks or other flaws. It must be able to take and hold a fine smooth edge. It must not have a feather edge, that is, an edge which will easily turn over or break and give the appearance of a saw edge. This requires that it shall possess to a high degree both hardness and toughness. The difficulties of the problem are increased due to the fact that the composition and heat treatment which gives a maximum hardness does not at the same time give a maximum toughness. The cutler must, therefore, determine upon a suitable compromise which will yield a satisfactory combination of hardness and toughness. Experience has shown that the best combination of properties is obtained by quenching the steel from above the critical temperature and drawing it to a temperature which depends upon the dimensions of the blade and the work for which it is designed.

If the quenching is too severe cracks are formed in the blade. In practice, these cracks are usually not noticed until a relatively large amount of work has been performed upon the blade. It is generally only after the blade has been ground and polished that the cracks become visible. If in the effort to avoid cracks the quenching process is made less rigorous, then the resulting hardness is insufficient. The drawing operation increases the toughness but does so at the expense of the hardness. From the magnetic standpoint the investigation of the problem of testing knife blades is twofold: (1) to determine the magnetic characteristics of a finished blade which possesses the necessary mechanical properties; (2) to determine the magnetic characteristics of heat-treated blades in the rough which may be used as criteria in separating the cracked blades from the good ones.

Extensive tests on knife blades, both finished and unfinished (quenched) have been conducted, but will not be described in this paper. The purpose of the investigation has been to throw light upon the possibilities of magnetic analysis in the testing of knife blades. Time has not been taken to examine very deeply the different methods of attack beyond showing that they are practicable. The determination of their relative merits belongs to the development of the details of commercial methods of handling the testing. As far as the data of the present investigation are concerned the following conclusions may be drawn.

1. The proper hardness of the finished knife blade may be determined in terms of its coercive force. This criterion will sort out the defective material from the good and will indicate whether the blade is too soft or too brittle. It will classify good blades in their order of merit. Thus we have a means of telling definitely whether or not a blade is of the highest grade. Furthermore this test does not injure or mar in the slighest the highly polished finished blade. The advantages of such a test are at once evident.

2. A magnetic examination of a blade as it comes from the quenching bath will tell whether or not the blade is cracked or has been so badly strained in quenching that cracks are liable to develop under further thermal or mechanical handling. Such a test will enable a manufacturer to throw out the wasters before they have been subjected to more or less expensive mechanical work. Occasionally a blade or series of blades are underquenched. The same test that will detect overquenching will detect underquenching. The underquenched material can be at once retreated without loss of further time or labor.

3. If it is desirable to detect material that has been burned either by grinding or finishing it may be done by a suitable examination before and after the mechanical operations. Possibly a single magnetic test would suffice if sufficient care is taken in the heat treatment.

4. The problem of magnetic analysis of knife blades that remains to be worked out is the determination of which one of a half dozen or over magnetic criteria will give the *best* results from a commercial standpoint. The possibility of a suitable test is beyond question.

5. Suitable methods for rapid shop testing must be developed, the details of which will depend in great part upon the results required, and the amount of testing to be performed.

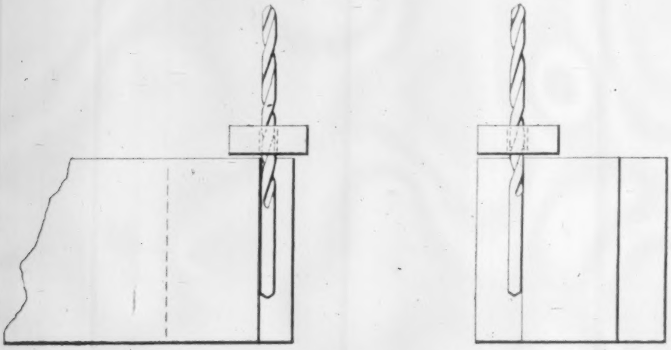

FIG. 20.—Mode of Applying Drills to Permeameter.

Drills.—A number of small drills (No. 39) were examined magnetically by placing them against the test coil yoke of a Fahy permeameter as shown in Fig. 20. The magnetic data are given in Table VII. The most noticeable fact is that the order of increasing coercive force is identical with the order of increasing file hardness. The mean value of the coercive force for eight specimens as received and which presumably are correctly hardened is 17. The difference between this value and 10, the value of coercive force for the annealed specimen, is so great that there would be no trouble in separating properly treated drills from those which had accidentally received no heat treatment. Those which have been quenched but not drawn and which therefore are excessively brittle are distinguished with equal facility from the properly treated drills. Thus the coercive force not only separates the good from the bad drills but also arranges the good drills in their order of merit.

The two drills designated as E and 4, which were quenched in water and oil, respectively, are worthy of consideration. They are only slightly different in coercive force and show small corresponding differences in file hardness. As far as the coercive force indicates, then, these two drills are substantially equivalent. The difference which we know must exist between the water-quenched and oil-quenched specimens is shown by the induction B or what is proportional to it, the permeability. Whether this difference is characteristic can only be determined by further investigation. For the present, it is enough to say that differences exist between steels of different heat treatment.

TABLE VII.—SHOWING THE MAGNETIC CHARACTERISTICS OF DRILLS 62 MM. (3.4 IN.) LONG AND 2.5 MM. (0.098 IN.) IN DIAMETER.

Specimen.	Condition.	B	B_r	H_c	File Hardness.
3	Annealed	52.8	12.4	10	1
C	As Received	56.3	17.1	15	2
H	"	54.4	18.4	16	3
F	"	52.7	18.5	17	4
5	"	49.4	16.8	17.1	5
G	"	54.1	17.9	17.3	6
2	"	51.6	17.6	17.7	7
E	"	54.9	18.7	18.0	8
4	"	54.8	18.6	18.2	9
E	Quenched in Water	46.0	16	24.0	10
4	Quenched in Oil	37.7	13.3	24.4	11
Mean of "As Received"				17.0	
Mean of Quenched				24.2	

APPLICATION OF LEAKAGE TEST.

Inhomogeneities in Steel Rails.—It has been shown in the preceding pages that there is a close relationship between the magnetic and other physical characteristics of steel. Only by a magnetic examination are we able to determine by a nondestructive test whether or not two pieces of steel are identical in properties. Not only may we compare the properties of two individual bars but we may also determine whether two portions of the same bar are identical. In other words, it is possible by a magnetic test to determine whether a given specimen is homogeneous along its length. Inhomogeneities may be due to blowholes, pipes, fissures, segregation, strains, and other causes.

In the investigation of inhomogeneities in magnetic material, three distinct problems are involved. First, a suitable method of magnetic examination must be developed. Second, it must be determined whether observed variations in the magnetic properties are accompanied by corresponding mechanical variations. Third, it must be ascertained whether the observed magnetic quantities, or their variations, are of such magnitude as to locate all dangerous mechanical defects. The experimental procedure depends in a large measure upon the nature of the material and the dimensions of the specimens to be examined. The steel rail is one of the simplest forms of material suitable for magnetic examination, as well as one of the most important from a practical point of view.

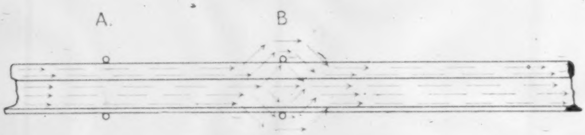

FIG. 21.—Showing Magnetic Leakage Effect in a Steel Rail which has a Region B of Greater Magnetic Reluctance than Other Portions of the Rail.

Several methods of magnetic examination of rails have been developed, and are very briefly referred to.

Total Magnetic Flux Method.—Fig. 21 represents the distribution of magnetic flux in a steel rail which has a region *B* of greater magnetic reluctance than other portions of the bar. Because of this magnetic hardness the flux within the rail is less at *B* than at the adjoining sections, as at *A*.

These magnetic differences along the length of the rail may be measured in several ways. One of the simplest methods is to measure the magnetic flux at intervals along the length of the rail for a definite value of the magnetizing force. These values will be equal if the permeability and cross-section of the rail are constant.

It is quite difficult, however, to produce a uniform magnetizing force along any considerable length of the rail. In general the magnetizing force varies slightly from point to point. The magnitude of this variation depends upon the distribution of the magnetomotive force and the shape of the specimen.

In general we may write

$$\phi = \mu A H \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where, ϕ = total magnetic flux, μ = magnetic permeability, A = cross-sectional area, and H = magnetizing force. If μ, A, and H are constant, ϕ also is constant. Any variations in permeability or cross-sectional area are indicated graphically by deviations from the straight line graph of Eq. 1. Such variations represent magnetically hard spots, at which either the permeability is lower or the cross-sectional area less, due to differences of external dimensions or the presence of internal cavities.

This method while it seems very simple has several disadvantages. In the first place the quantity to be measured is the whole magnetic flux while the only factor that is indicative of inhomogeneities is the variation of this magnetic flux at different cross-sections along the length of the rail. A second disadvantage is the large e.m.f. of self induction induced during the reversal of the magnetizing current. The third serious objection lies in the large time constant of the magnetic circuit. Because of these objections the method involving the measurement of the total magnetic flux will not be considered further.

Magnetic Leakage Method.—The objections to the preceding method are overcome by measuring directly the variation in the magnetic flux along the length of the rail, which is the "magnetic leakage." If a single test coil is moved along the rail from its initial position to a new one, the magnetizing current being maintained constant, the resultant electromotive force induced in the test coils is proportional to the product of the magnetic leakage between these two positions and the rate of displacement. The time integral of this e.m.f., which is a measure of the leakage, may be measured by a ballistic galvanometer. If the rate of displacement of the coil along the rail is constant, the electromotive force is proportional to the magnetic leakage and may be measured by a suitable galvanometer.

Rate of Change of Leakage Method.—This method is similar to the "magnetic leakage" method in that the magnetizing solenoid and the test coil move along the rail, but differs in that it has two electrically opposing test coils separated from each other by a short distance instead of only one test coil. The quantity measured is the space derivative of that measured by the magnetic leakage method, and is called the "change of leakage" method.

Description of Apparatus.—In an earlier form of apparatus, the magnetomotive force is supplied by four solenoids each 30 cm. long and having approximately 2400 turns each. The solenoids are connected in parallel, and the current is supplied by a storage battery of 120 volts. The test coil is wound on a form which closely surrounds the rail, with only a small air space between the windings and the rail. When two test coils are used, they are both wound on the same form and separated from each other by about two centimeters. The magnetic circuit consists of the rail under test and a similar companion rail placed side by side with their ends joined by massive iron yokes so as to form a closed magnetic circuit. In addition to the flux that passes from one rail to the other by way of the connecting yokes, there is a heavy leakage flux through the air.

A later form of apparatus consists of a single solenoid moving along the rail under investigation. Instead of a companion rail, the return magnetic path is through a massive steel beam. This arrangement, which is shown in the photograph of Fig. 22, has several advantages over the one just described. In the first place it is not necessary to have an auxiliary rail of substantially the same size and material as the rail under test. Secondly, the magnetic return path is of lower reluctance due to greater cross-section and higher permeability. This latter advantage, however, is counteracted in large part by the fact that no magnetizing coils surround the return magnetic path. If it should prove desirable, such coils could be added and left permanently in place. Thirdly, it reduces the amount of time and labor required in getting the test rail in place.

An arrangement which was not tried in the laboratory but which might offer advantages if such tests were to be made on a commercial scale is to maintain the coils in a fixed position and to move the test rail through the coil.

Recording Apparatus.—The record of the voltage induced in the test coil is taken photographically. A photographic film mounted on a drum which is rotated by means of an electric motor, receives the image of a spot of light reflected from the galvanometer mirror.

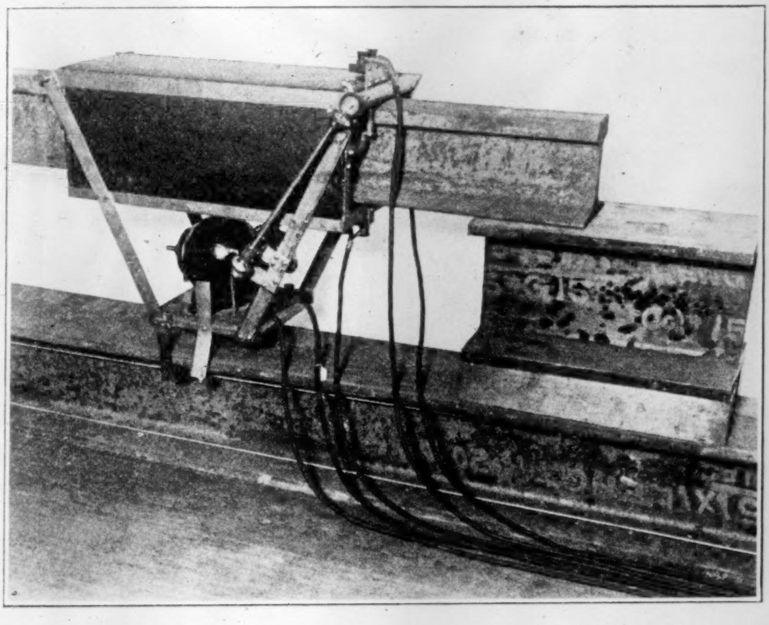

FIG. 22.—Traveling Carriage of Rail Permeameter; Later Form.

Experimental Work.—In the development of this method of magnetic exploration the test material consisted of two rails. One was a 30-ft. length of a 100-lb. rail, which was sawed in half and the two halves designated as A and B. The second sepcimen was a 20-ft. length of an 80-lb. rail designated as rail C.

Specimens A and B are from the same heat as another rail which broke in service and caused a wreck. Rail C broke in service and caused a wreck.

These rails were examined as received and also after they had been given certain artificial flaws such as drill-holes and saw-slots. The results of these tests are only briefly summarized in the present paper.

The following points were noted in the magnetic examination of rail specimen A:

1. The rail shows a number of pairs of relatively hard and soft spots, equal in number to the number of ties upon which the rail rested.
2. The maximum magnetic hardness corresponds very closely with the centers of the portions resting on the ties.

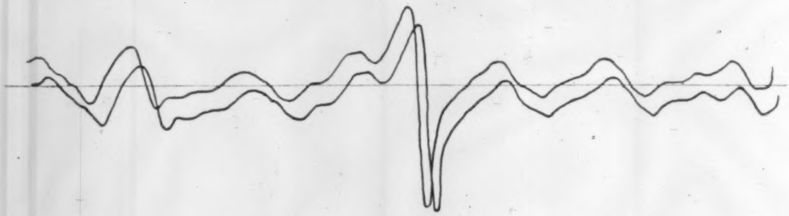

Fig. 23.—Magnetic Exploration of a Rail with a Transverse Saw Slot in the Head.

3. A saw slot in the base of the rail shows a decided magnetic hardness.
4. Near the end containing the splice bar holes is a region of relative magnetic softness.

A saw slot about 1 mm. wide was cut across the head of specimen B. The artificial defect thus produced removed about 10 per cent of the cross-section of the rail. In order to reduce the effect of the reduction in metal this slot was filled with strips of high permeability transformer steel. An effort was thus made to simulate the condition of a transverse fissure.

This rail was then studied magnetically by means of the two opposing test coils moved at a uniform rate along the length of the rail while the magnetizing solenoids moved with the test coils.

The effect of the saw slot is quite marked in each of the records. The records made with the larger magnetizing current show a great deal more detail than those made with the smaller current.

The consistency between the details of two different records is shown on Fig. 23 which contains two records slightly displaced from each other so as to avoid confusion. The two curves show the same characteristics and differ only in magnitude and minor detail. Such differences may be easily accounted for by slight variations in the speed of the carriage.

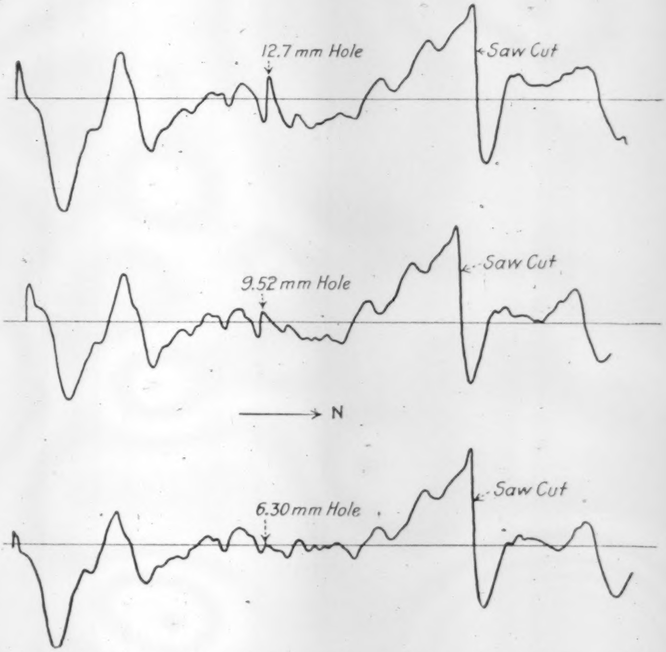

FIG. 24.—Photographic Record of Inhomogeneities in a Standard Steel Rail after Service, showing the Effect of Artificial Flaws.

To determine whether this method would detect a flaw in the web of a rail, records of the magnetic condition were made with holes drilled in the web of the rail. Records were taken after holes of various sizes had been drilled and are shown in Fig. 24. The arrow head indicates the position of the hole. It is quite evident from these curves that such a defect does make its impress on the magnetic record. An increase in the size of the hole increases the prominence of the magnetic indication.

The most striking characteristic that appears in all of the records, no matter how taken, is the periodicity of the magnetic charges along the length of the rail. Curve A, Fig. 25, for instance, shows a series of nine magnetically hard regions in rail C, rather regularly spaced. A visual examination of the rail shows that in this same region the rail rested upon nine ties. The location of the ties is readily determined from the different degree of rusting which has taken place on the rail where it touched the tie and in the space between ties.

If we make the justifiable assumption that a new rail would not show such regularly spaced magnetic non-uniformities, we are led to the conclusion that the presence of the ties and the other service conditions have produced changes in the structure of the rail. A further comparison of curve A and the tie marks shows that the position of maximum magnetic hardness comes in the region between the ties. This magnetic hard region is not midway between the ties but is nearer the edge of the tie which is toward the broken end of the rail.

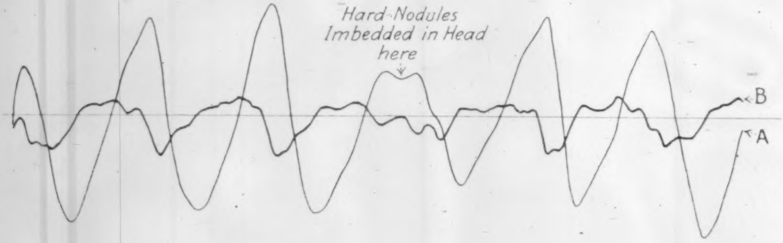

FIG. 25.—Showing Photographic Records of Magnetic Condition of Rail showing Tie Marks. Curve A with One Test Coil. Curve B with Two Test Coils.

It would be very desirable to have mechanical tests made on the rail to determine if mechanical differences exist which correspond to the magnetic differences. Sections from the head, web and base should be examined magnetically to determine whether the magnetic homogeneities are confined to one portion of the rail or are distributed throughout the section.

MAGNETIC SURVEYS ON NEW AND FAILED RAILS.

By P. H. Dudley.

SUMMARY.

Magnetic analysis of various grades of finished steel articles has received attention and development in the past few years.

The Rail Problem.—Induced interior transverse fissures have developed in several rail heads under service the last decade. There is no indication at the mills of the checked nuclei, or injuries of the interior metal in the rail heads by the gag applied to straighten the rails.

Railroad officials from service records of rails of different manufacture find that those from reheated blooms develop hardly any interior transverse fissures, while rails rolled direct from the ingots develop numerous fissures. Eight railroad companies reported 322,593 tons of rails rolled from reheated blooms with only 59 failures, and 559,644 tons rolled direct with 1054 failures. To reheat the blooms is a remedial process.

Tests.—Inhomogeneity of the physical properties of the interior metal of the rail heads has been found by physical tests and confirmed by magnetic surveys made as described in the paper.

It would seem from the indications of defective metal found in the rail heads by magnetic analysis, that other railroad companies are warranted in making similar investigations to find the occasional defective rail rolled direct before it is laid in the track.

Research.—Magnetic surveys furnish a fund of information impossible to secure by any other method without destruction of the material. Special designs and constructions of apparatus must be made to test such parts as axles and connecting, parallel and piston rods for locomotives. It will be possible at the same time to study the fatigue of metal and its "restoration."

MAGNETIC SURVEYS ON NEW AND FAILED RAILS.

By P. H. Dudley.

Introduction.

Magnetic analysis of various classes of finished and semifinished steel products has received consideration, extensive investigation and development during the past few years. The advantages of this type of testing were early recognized and utilized in a number of practical investigations. A general and thorough discussion of magnetic analysis was presented before this Society by Dr. C. W. Burrows at the 1917 annual meeting.[1] The same author has also furnished a fund of valuable data correlating the physical and magnetic properties of materials.[2]

The first equipment for surveys of rails was developed at the Bureau of Standards under the direction of Doctor Burrows and efficiently operated. The apparatus designed by the writer, with the assistance of Mr. H. A. Currie and his assistant, Mr. H. C. McMillan, of the Electrical Department of the New York Central, for the present investigation embodies all of the essential and principal details of the Bureau of Standard's equipment except for a few minor changes which were necessary under the circumstances in which our tests were conducted.

The Rail Problem.

There have developed several cases of induced interior transverse fissures in rail heads under service conditions in the present decade of railroad operations. These have been improperly designated "transverse fissures," a term which does not express their location or origin in the interior metal of the rail head. The checked nuclei are invisible to the inspectors of the rails at the mills and to the section men and supervisors in the track. It needs magnetic vision to find them in the rail heads as fabricated.

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[1] C. W. Burrows, "Some Applications of Magnetic Analysis to the Study of Steel Products, *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 87 (1917).

[2] "Correlation of the Magnetic and Mechanical Properties of Steel," *Scientific Paper* No. 272, U. S. Bureau of Standards.

The Division of Safety of the Interstate Commerce Commission, from its investigations, classifies them as "fatigue fractures of metal" due to the wheel loads, and holds that all rails are subject to them. The remedy it proposes is to reduce the wheel loads. This recommendation was made before collecting the service records for rails of different methods of manufacture to see whether or not all were affected alike. The railroad officials, from their records of the service of various rolling of rails, find that those rolled from reheated blooms are nearly free from interior transverse fissures. They find that rails of the same section when rolled direct from the ingots, laid on portions of the same roadbed, and under the same wheel loads, develop a greater number of interior transverse fissures.

Eight railroad companies under heavy traffic reported from their service records 322,593 tons of rails from reheated blooms in which only 59 induced interior transverse fissures developed in the rail heads. Their records also included 559,644 tons of rails by direct rolling in which 1054 induced interior transverse fissures developed, an increase of 900 per cent over those in rails from the reheated blooms. These rails were rolled in 1909 to 1915 inclusive, while the records of fissures were to October, 1918.

Such a difference in the service of rails under practically the same wheel loads is evidence to railroad officials that there is some inhomogeneity of the physical properties in the metal of the interior of the rail heads—particularly those rolled direct—which induce the interior transverse fissures, compared to interior metal from those rail heads which do not develop such fissures in similar service.

The paramount question with railroad officials is "Safety First," and hundreds of the failed rail heads have been tested under the drop for brittleness, also tension tests made of the metal of the interior of the head which show a loss of ductility of the metal compared to the enclosing envelope of exterior metal. Delayed transformations have been found by heating and cooling curves; and cores of abnormal metal first on one side of the center of the head which changed to the opposite side of the head in a few inches of length. Well-developed polyhedral crystals have been found as the nuclei of interior transverse fissures which indicate that a germinative temperature existed a sufficient length of time for their development; 132 rails were cut in small pieces, and well-developed crystals were found in 22.

These facts were found only after destruction of the rails. Similar tests could be made only from pieces cut from the top or bottom of the rail crops which do not go to the hot beds to cool, and therefore are not representative of the occasional rail on the hot beds which fails in the track.

It is this feature of magnetic analysis without destruction of the section which offers the probability of detecting and eliminating the occasional rail which was rolled direct, before it leaves the mill or is put in the track.

Fig. 1 is an illustration of the more predominant type of induced interior transverse fissures and is classified under the name of "Intergranular." The photograph shows clearly that the fracture of the rail is made up of three separate and distinct parts, namely:

1. The nucleus, or central intergranular area;
2. The lustrous detail development surrounding the nucleus;
3. Fracture of the balance of the rail which occurs quickly after the fissure has developed sufficiently to impair the strength and integrity of the rail section. Each distinct fracture occurs only in widely separated periods of time.

The lustrous detail fracture through the grains is the progressive growth or development from the nucleus, and is now universally recognized as being due to the bending action of the rail under the passage of many thousands of wheels. The problem is therefore reduced to the study of the character and cause, in rails which are rolled direct, for the fracture of the nucleus. Except in rare cases of this type, no interior detail fractures have developed without having started from the characteristic intergranular nucleus which is illustrated in Fig. 1.

Numerous tests have shown that the essential characteristics of the metal in the vicinity of the nucleus are low tensile strength, brittleness, and a practical absence of ductility. The character and appearance of the nucleus furnish positive evidence of its method of failure. Examination discloses that fracture of this intergranular area occurs suddenly, the whole area which is sometimes as large as $\frac{3}{8}$ in. in diameter failing as a unit. This is produced by the application of a concentrated overload of sufficient magnitude to cause sudden fracture.

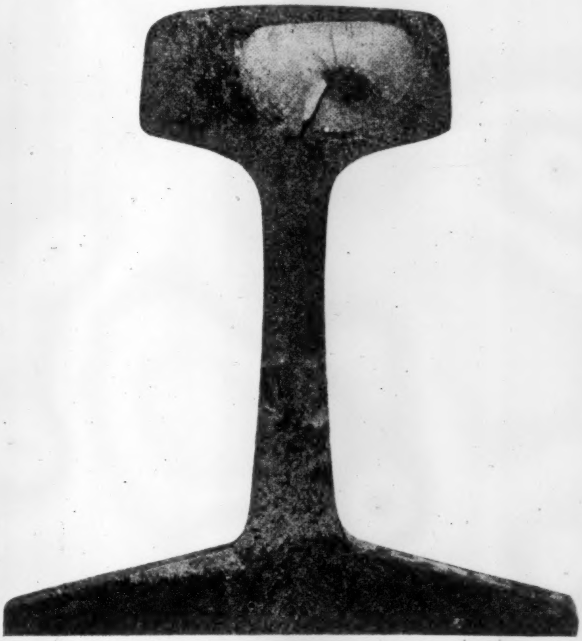

FIG. 1.—6-in. 100-lb. rail ($\frac{9}{16}$ size) which shows in the head an Interior Transverse Fissure, Intergranular Type. The nucleus is large, $\frac{7}{16}$ by $\frac{5}{16}$ in. in outside of head where about 21 per cent occur in this brand and section. Rail rolled direct, Jan. 16, 1911, in cold weather.

To explain how the overloads at the mill occur, the hot 105-lb. rails are sawed 33 ft. $6\frac{3}{4}$ in. to shrink to 33 ft., then cambered—the head curved around the base—and run to the hot beds, where as they cool, recalesence of the base occurs, which expands it around the head. Then the head undergoes recalesence and expands around the base more than the original camber. When the rails cool to atmospheric temperature, they are expected to be nearly straight. This is never the case and the rails must be gagged to make the surface and line suitable to be laid in the track. The operation under the straightening press consists of applying the gag on the rail to produce permanent sets where needed at intervals along its length, but in so doing, harmful impact stresses of an intensity of 100,000 lb. per sq. in. and over are frequently imparted to the metal in the interior of the rail head. The severity and magnitude of overloading during gagging depends upon the physical condition of the metal in the interior of the head and the curvature of each rail as received for straightening. Metal with a tensile strength below the delivered impact stress in the rail head is therefore liable to be fractured. This weak interior metal when fractured provides the checked nucleus from which the induced interior transverse fissure subsequently develops in service. Overloading during straightening is sometimes so severe that the rail section is completely fractured.

Numerous efforts have been made to eliminate the destructive effect of gagging. It is possible to effect a reduction in the amount of pressure transmitted in the rail by increasing the span of the supports in the press. Thus, 50,000 lb. less pressure is required to straighten 6-in. 105-lb. rails on supports of 60-in. span than on supports of 42-in. span, which is the present mill standard. The solution of the problem in the mill then consists of two parts:

First, the avoidance of brittleness of the metal, by proper chemical composition and manufacture;

Second, the reduction of the destructive and injurious effect of gagging, which now has the cooperation of several steel plants, by widening the supports to 60 in. for stiff sections.[1]

To make the magnetic surveys of rails, the required sensitiveness of the galvanometer must be ample to record a checked nucleus in a new rail from the straightening press. The new rail would only have the checked nuclei and the combined effect of the gag, without any development of the specular surfaces; therefore the sensitiveness must be sufficient to detect these in the leakage curves before they are put in the track.

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[1] The effects of gagging on the rails to straighten the line and surface must be remembered in any investigation of interior transverse fissures.

We have approximated the required sensitiveness of the galvanometer from the magnetic surveys of the other portions of rails which have failed. Where marked oscillations have occurred, we have broken the rails under the drop and found checked nuclei from which induced interior transverse fissures had just started to develop. This work is being repeated on failed rails, and the records are accumulating for comparison and study.

Investigations are being made of the rails from reheated blooms which develop in the track induced interior transverse fissures. The results indicate that the final temperature of the bar as rolled is too low to accomplish what reheating the blooms usually does to the interior of the metal in the rail head. This may be due to some delay in rolling the bloom in one or more passes before the finishing. There is one mill which reheats the blooms concerning which we have yet to hear of a single interior transverse fissure in its large output, and another mill which has only one against its output.

To raise the hot blooms of the ingot as an intermittent step to a wash heat of 2300° F. (1260° C.) is a practical remedial mill practice to eliminate the inducing cause of interior transverse fissures in the interior metal of the rail heads. The practice of reheating blooms is old, coeval with the process of making Bessemer steel rails and still retained by several manufacturers of open-hearth steel rails. The reheating furnaces were omitted in the construction of one Bessemer mill in the eighties and of another mill in the nineties of 1800. They were omitted also in some of the modern mills for open-hearth rails. One of these mills installed reheating furnaces some five years ago, and the subsequent output of rails has been nearly free from interior transverse fissures.

This statement of fact regarding the freedom from interior transverse fissures of rails rolled from reheated blooms does not, of course, explain how reheating improves the interior metal of the rail heads. The necessity of prompt action, however, requires that we first heed the facts and act, then investigate the reasons at more leisure. The inability during the past year to secure rails rolled direct from one ingot and from reheated blooms from the next ingot of the same heat, has for the time being prevented comparative magnetic investigation of the interior metal in the rail heads by these two methods of manufacture.

The magnetic surveys of rails by the railroad companies will be confined at first to those rails which are rolled direct, as the reheated blooms develop comparatively so few of the induced interior transverse fissures in the track.

There is also the application of magnetic surveys to the detection of defective rails of this type which may be in our tracks. Several practical difficulties must be investigated and surmounted to locate defective rails in the track by either magnetic or electrical apparatus which will take time for research and development. We have therefore confined our efforts at first to the development and use of equipment which is suitable for either laboratory or mill work, though the problem of detecting faulty rails in service has received considerable study.

APPARATUS AND METHOD OF TESTING.

Fig. 2 illustrates the general set-up of the equipment. It consists of a bottom supporting member, which is a 33-ft. rail turned base up; two sections of rail 12-in. high which act as vertical supports; and the test rail which forms the top and closing member of the yoke. The energizing or magnetizing solenoid travels along the test rail at a uniform rate, and is driven by a motor mounted above, and direct geared to the brass drive roller. Search coils are concealed within the solenoid shell for the detection of variations in the permeability of both the rail head and base, and are separately connected to the galvanometer circuit.

Fig. 3 illustrates the general connections. Following are some data on the equipment and its characteristics:

Dimensions of solenoid..	6 by 6⅜ by 24 in. long.
Magnetizing force......	10,000 ampere turns.
Voltage...............	60 volts.
Current...............	4.72 amperes.
Total number of turns..	2,120
Length of winding......	4,840 ft.
Size of wire............	No. 13 D. C. C.
Batteries..............	Willard, 5 crates of 6 cells each.
Drive motor............	Eck. ⅙ h.p.
Galvanometer.........	Leeds & Northrup—Type R. No. 2500.
Search coil............	50 turns of No. 30 D. C. C.

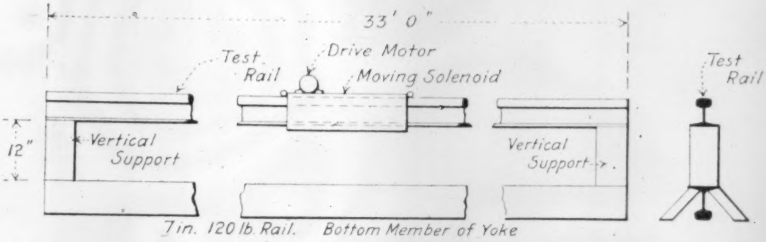
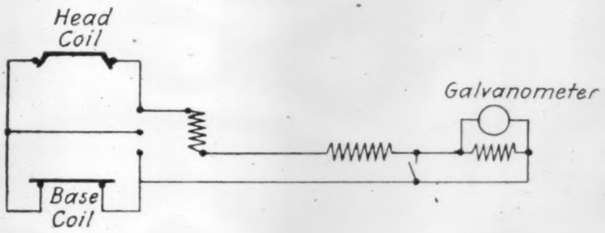
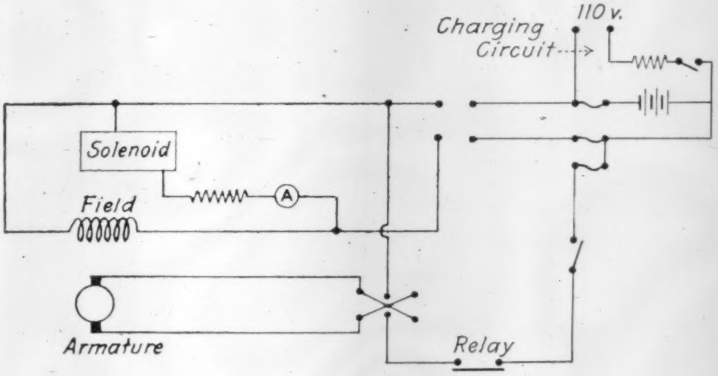

33' 0"
Test Rail
Drive Motor
Moving Solenoid
12"
Vertical Support
Vertical Support
Test Rail
7 in. 120 lb. Rail.
Bottom Member of Yoke

FIG. 2.—Diagram of Apparatus for Magnetic Survey of Rails.


Head Coil
Galvanometer
Base Coil

Search Coil and Galvanometer Circuit.


110 v.
Charging Circuit
Solenoid
Field
A
Armature
Relay

Magnetizing and Driving Motor Circuit.

FIG. 3.—Diagrammatic Views of Magnetizing and Other Circuits in the Apparatus.

Permanent records of the surveys are obtained by reflecting a beam of light from the galvanometer mirror into a special camera box which contains a moving strip of film.

The conditions under which all surveys are made are maintained standard so that the records are comparative one with another. All tests and surveys have been conducted in the Electric Shops of the New York Central Railroad at Harmon, N. Y. No tests have been made either at the steel plants or out on the tracks.

The reliability, accuracy and consistency of magnetic surveys on steel rails have been checked by duplicate curves. We have made over 1000 observations, together with 217 permanent records on 60 new and 56 failed rails, typical records being shown as Figs. 4 to 9 inclusive. Surveys have been successfully conducted on sections of 80, 90, 100 and 105 lb. in weight, and in lengths of from 8 to 33 ft., necessitating only one slight change in the standard equipment for all sections. The expense involved in making the surveys is small, the time required to test each rail is moderate, and the equipment requires a minimum amount of space and can be quickly dismantled and moved. We have made numerous complete surveys on rails in 25 minutes, one-half of the time being required for handling the rail on and off the vertical supports. This time can be further reduced when changes in methods of handling and making surveys are instituted.

The permanent records obtained are complete histories of each rail, and furnish information which is not secured by any other method of testing. No machine work or special preparation of the rails to be tested is necessary, and furthermore the characteristics and quality of the material are obtained without destruction of the rail. The superiority of magnetic testing in this respect is marked when compared to tension testing. The latter requires time and expense for preparation of specimens, destruction of the material tested, and at best furnishes information on only about 4-in. in the length of the rail.

SURVEYS ON NEW RAILS.

Surveys and permanent records have been secured on 60 new rails. These have been placed in the tracks and will be subjected to heavy traffic for a period of service. At a later date, they will be removed and surveyed for the purpose of checking the previous surveys and to note any changes which may have occurred.

Typical records are presented in Figs. 4 to 7, inclusive. The chemical and physical properties of the rails, which were the 6-in. 105-lb. Dudley type, have been determined, and a careful and complete set of observations were obtained in the mill of the conditions under which the rails were manufactured.

A number of ingots were selected and all four rails of each one have been surveyed in order to determine the variation in characteristics of the metal from the top to the bottom of the ingots. The differences noted were slight and are almost entirely masked by the greater disturbances produced where the gag was applied in straightening the rails.

Rails have been surveyed which were straightened on 42 and also 60-in. supports. The marked reduction in the magnetic disturbance is readily apparent when the longer span supports are used, as will be seen by an examination of Figs. 4 to 7. The position of the blows which were applied to the rail are located on the records and were originally determined at the mill by our inspectors. The greatest oscillations occur where the overloading and overstraining action of gagging was greatest. The degree or magnitude of the magnetic disturbances is an indication of the degree of the physical disturbance, for the two disturbances are correlated.

Head and base records are shown on each of the figures. These curves were taken separately, not simultaneously, although they are shown together on the same film. There is a marked similarity between the curves for the head and base, which is accounted for by the fact that the disturbing action of straightening is transmitted through the entire rail section. The oscillations in the base records are consistently lower than those recorded for the head. This is true whether the blow on the rail during straightening was imparted in the head or base. The difference in the magnitude of the oscillations is accounted for largely by the dissimilarity in shape of the rail head and base, also the shape of the two search coils, and furthermore by the fact that the metal of the base is of a more uniform and finer texture than that in the head.

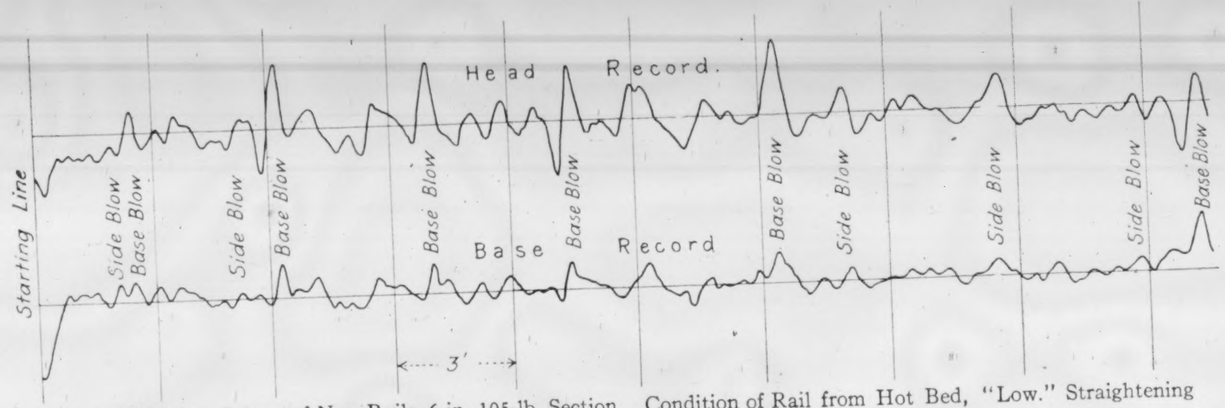


FIG. 4.—Leakage Curves of New Rails, 6-in. 105-lb. Section. Condition of Rail from Hot Bed, "Low." Straightening Press Supports, 42-in. Span.

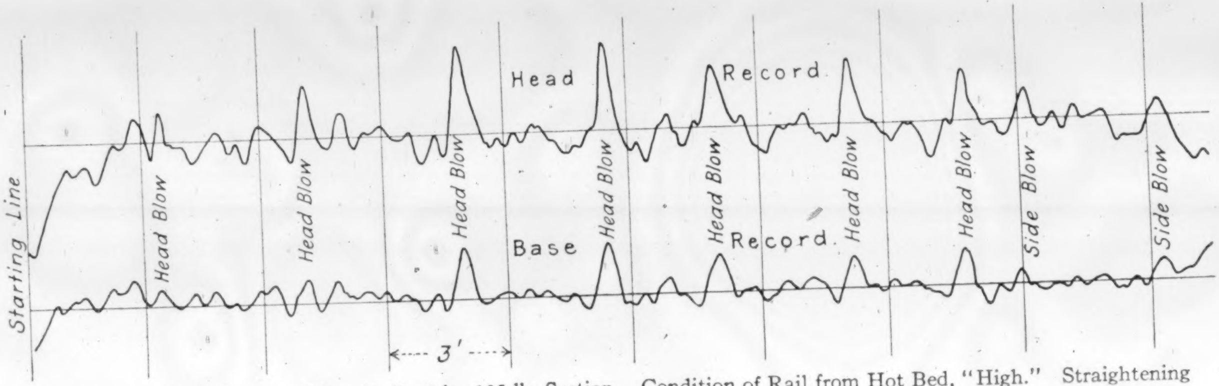


FIG. 5.—Leakage Curves of New Rails, 6-in. 105-lb. Section. Condition of Rail from Hot Bed, "High." Straightening Press Supports, 42-in. Span.

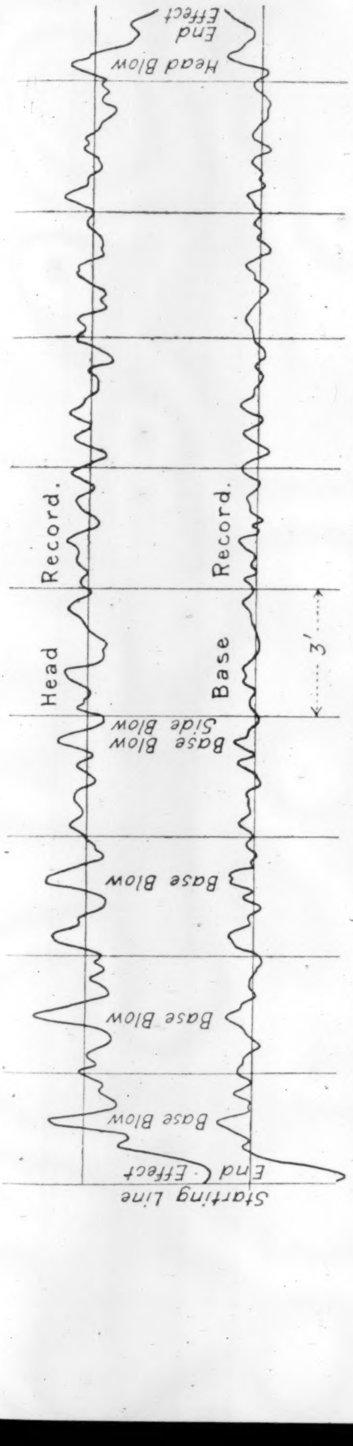


FIG. 6.—Leakage Curves of New Rails, 6-in. 105-lb. Section. Condition of Rail from Hot Bed, "Low." Straightening Press Supports, 60-in. Span.

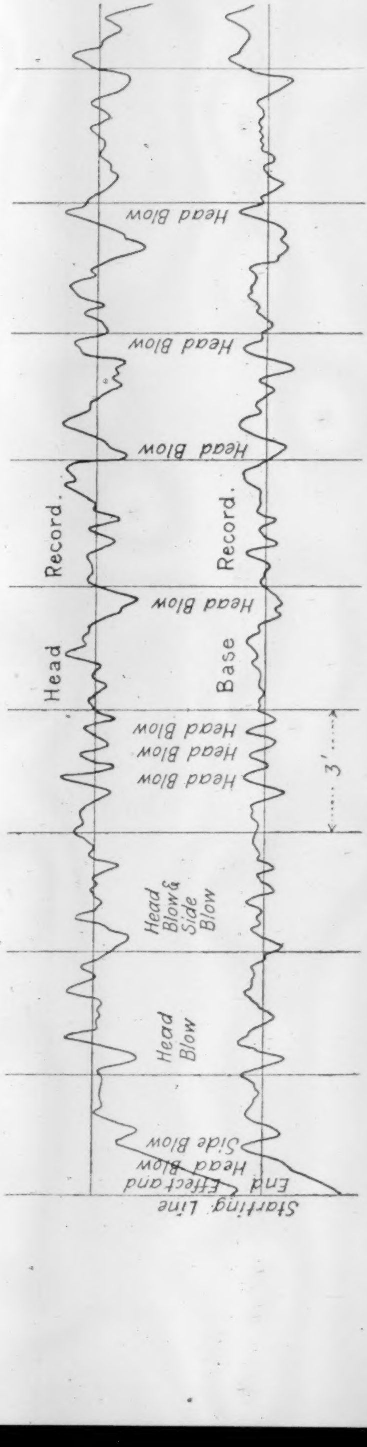


FIG. 7.—Leakage Curves of New Rails, 6-in 105-lb. Section. Condition of Rail from Hot Bed, "High." Straightening Press Supports, 60-in. Span.

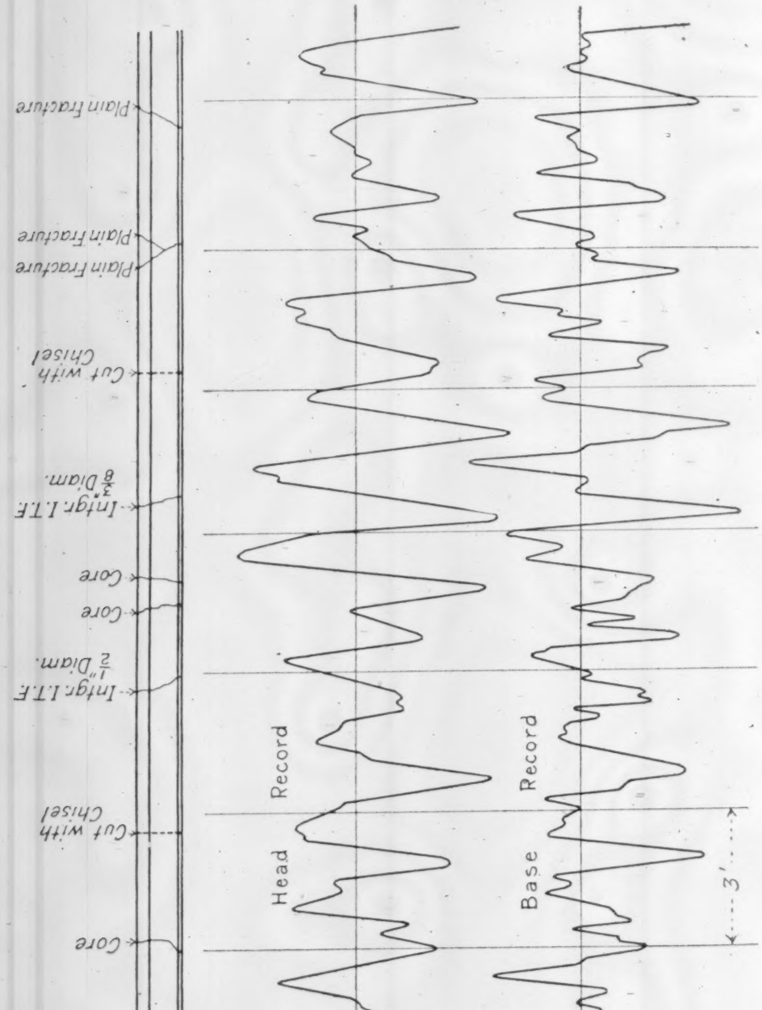


FIG. 8.—Leakage Curves of Failed Rails, 5⅛-in. 80-lb. Section.

The "condition of the rail" referred to in Figs. 4 to 7 pertains to the camber or sweep remaining in the rails after cooling to atmospheric temperature. "Low" rails are those in which the base is curved around the head, and require "base" blows to correct the rail's surface. "High" rails are those in which the head is curved around the base, and require blows on the head to correct the rail's surface. "Side" blows are also imparted to the rail to remove the side curvature and correct the rail's line, but these blows are light and of lesser importance, producing but slight magnetic disturbances as shown in the figures.

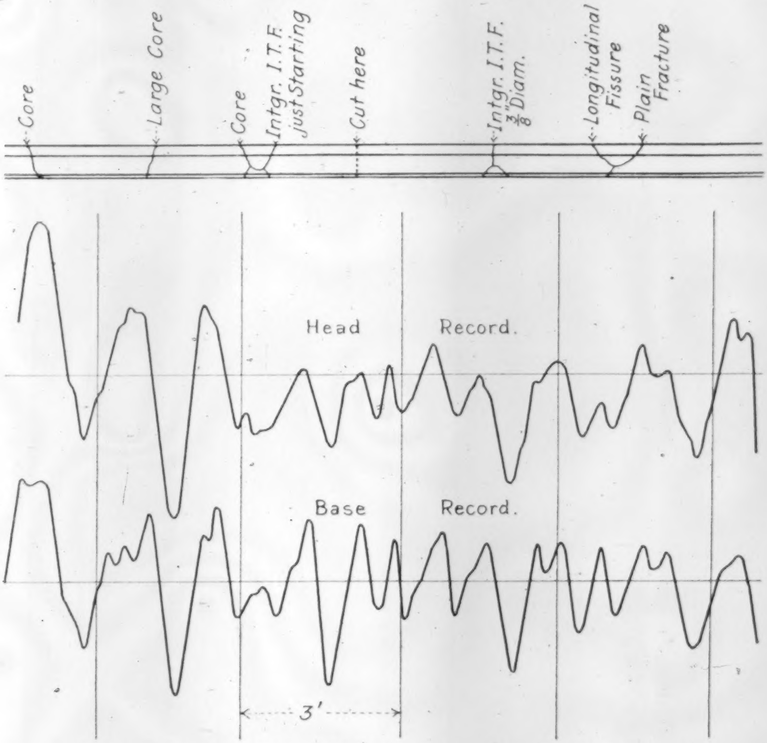


FIG. 9.—Leakage Curves of Failed Rails, 6-in. 100-lb. Section.

SURVEYS ON FAILED RAILS.

Surveys have been made on 56 failed rails removed from service after having developed interior transverse fissures.

Typical records are shown as Figs. 8 and 9. The oscillations are of considerably greater magnitude, although similar in character to those obtained on new unused rails. These rails were placed in service before the magnetic apparatus was made, therefore we do not have surveys to compare the original and final characteristics of the material.

These rails were taken to Beacon, N. Y., after the surveys had been made, where they were tested to destruction under a drop. This was for the purpose of disclosing any additional interior transverse fissures which might be contained within the rail heads, besides affording a check between the physical and magnetic characteristics of the rails. We were able, in a number of instances, to locate the interior transverse fissures definitely at the positions of the more violent fluctuations or oscillations. Substantiative proof was thus obtained from the character of the curves and the location of the interior transverse fissures that the overloading action of gagging was primarily responsible for the checking of the nucleus, and therefore definitely places the responsibility for the cause of their subsequent development as complete interior transverse fissures in service.

The record of the drop test is indicated on the record of the magnetic survey of each rail, so that a ready comparison can be noted between the location of the interior transverse fissures and the magnetic disturbances obtained in the surveys. The work thus far attempted warrants considerable confidence as to the possibility of locating faulty rails in service and thus permitting their removal before complete fracture of the rail occurs.

CONCLUSIONS.

The investigations which can be conducted on rail steel are large, and the work submitted in connection with this report is for the purpose of conveying an idea of the results thus far obtained. There are many features which are not touched upon in this brief report, but the investigations will be continued and broadened as the work progresses.

Magnetic surveys and analyses furnish a fund of information which cannot be secured by any other method of testing. The fact that the materials can be tested without destruction is of prime importance. It is this feature of magnetic analysis which makes it possible to find in advance those rails which after injury under the straightening press would develop in service into a complete interior transverse fissure.

It would seem from what has been accomplished already that other railroad companies are warranted in using similar apparatus to make magnetic surveys of their sections of rails which are rolled direct. Such surveys for the present can best be made by the railroad companies. Ample room and time are required to determine the brittleness or ductility of the metal in the interior of the heads of a number of rails of one section, A certain amount of ductility is necessary to meet the requirements of traffic under the climatic conditions of the location of the line.

Railroad service requires so many grades of steel with a wide range of physical properties in axles, crank pins, connecting, parallel and piston rods, rails, tires and wheels, that there are several opportunities to develop magnetic apparatus for testing them without destruction. It will also be possible at the same time to study the fatigue of metals and the restoration of their normal physical properties. To mention one example of restoration, several hundred axles which had been used for five years were immersed in an oil bath and raised to 600° F. for 6 to 8 hours, and they have since rendered five years additional service without a failure.

APPLICATION OF MAGNETIC ANALYSIS TO THE TESTING OF BALL BEARING RACES.

By R. L. Sanford and M. F. Fischer.

SUMMARY.

This paper is a progress report describing the preliminary experiments and presenting the results so far attained in an investigation undertaken with the end in view of making a practical application of magnetic analysis to the testing of ball bearing races. The results of work in the laboratory indicate that such an application has commercial possibilities.

APPLICATION OF MAGNETIC ANALYSIS TO THE TESTING OF BALL BEARING RACES.

By R. L. Sanford and M. F. Fischer.

Introduction.

The practical application of magnetic analysis consists of the utilization of magnetic methods for the nondestructive testing of steel and steel products under commercial workshop conditions. After the magnetic criterion for judging the quality of a particular product has been decided upon, there remains the problem of devising a satisfactory apparatus for making the magnetic measurements. The principal requirements of a commercial method are reliability, simplicity and ease of operation. It is not so important that the apparatus give accurate absolute values of the properties to be measured, as it is that differences be accurately indicated, since the test consists essentially of a comparison of individual pieces with certain others whose mechanical properties are known to be satisfactory and which therefore constitute standards of quality.

One of the important classes of steel products to which a practical application of magnetic analysis seems to be entirely feasible is that of ball bearing races. The pieces are of regular shape and apparently offer no insuperable difficulties in the matter of making satisfactory magnetic measurements. Furthermore, the present methods of inspection by mechanical methods are not entirely satisfactory. The two points which are most important in testing the mechanical properties of ball bearing races are the degree of hardness, and the homogeneity or freedom from flaws such as cracks or soft spots.

In taking up this problem, the Magnetic Laboratory of the Bureau of Standards has had the valuable and hearty cooperation of the Hess-Bright Manufacturing Company who, in addition to furnishing material for the investigation, have contributed technical assistance and special apparatus.

This paper is in the nature of a progress report for the purpose of describing the preliminary experiments and presenting the results already attained. The investigation is still in progress with the ultimate object of making a practical commercial application for the testing of ball bearing races in the factory.

COERCIVE FORCE MEASUREMENTS.

The results of previous work have indicated that the coercive force taken from a high value of maximum induction is a good index of the hardness of a steel object. The coercive force is the value of reversed magnetizing force necessary to reduce the magnetic induction to zero after the specimen has been magnetized to a certain maximum value of induction. The method employed for the measurement of coercive force makes use of the principle of the "magnetic potentiometer" which was originally described by Chattock.[1] The magnetic potentiometer consists simply of a test coil of constant cross-sectional area and having a uniform number of turns per centimeter, wound on a non-magnetic form. Chattock demonstrated theoretically that if the difference in magnetic potential existing between the ends of such a coil should be suddenly altered, the throw of a ballistic galvanometer connected to the coil would be proportional to the amount of the change. If the value of the product of the area by the number of turns on a test coil of this kind is determined, a means is thereby afforded for measuring the average strength of magnetic field between its ends. If a specimen is magnetized between the poles of an electromagnet, the magnetic induction can be measured by means of a ballistic galvanometer connected to a coil surrounding the specimen and the magnetizing force can be determined by means of the magnetic potentiometer just described.

The rings were magnetized between the poles of a DuBois electromagnet provided with special pole pieces. A test coil surrounded the ring for the measurement of the magnetic induction, B, and a test coil which did not surround the ring bridged the gap between the pole pieces for the measurement of the magnetizing force, H. Fig. 1 is a reproduction of a photograph of the electromagnet with specimen and coils in place. A diagram of connections is given in Fig. 2.

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[1] *Philosophical Magazine*, Vol. 24, p. 94 (1887).

The measurements were made in the following manner: With the specimen and test coils in place, the magnetizing current was adjusted to such a value that, upon reversal, the ballistic galvanometer connected to the H test coil indicated a magnetizing force of 200 gausses. Then the deflection due to the B coil upon reversal of the magnetizing current was observed. This reading gives the value of the maximum induction (B_m). The galvanometer was calibrated by means of the mutual inductance M and the sensitivity adjusted by means of the series resistances R_H and R_B so that the scale was direct reading. After the maximum induction had been determined, the residual induction (B_r) was measured by noting the change in induction when the magnetizing current was interrupted. The maximum magnetizing current was then reversed a few times to bring the specimen back to a cyclic magnetic condition. For measuring the coercive force the magnetizing force was simultaneously reversed and reduced to such a value that the

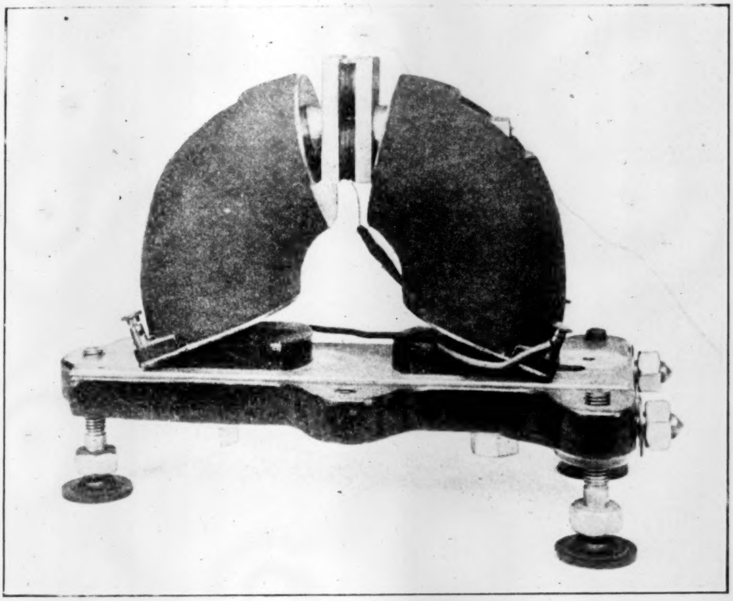

FIG. 1.—Electromagnet Arranged for Coercive Force Readings.

induction was just reduced to zero. The coercive force (H_c) was then read by opening the magnetizing current circuit while the galvanometer was connected to the H coil. A more accurate though less precise[1] method would be to measure the total change in H from its maximum in one direction to the value corresponding to the coercive force in the other direction. This is not necessary, however, as it was found that the magnetizing force due to residual magnetism in the core of the electromagnet

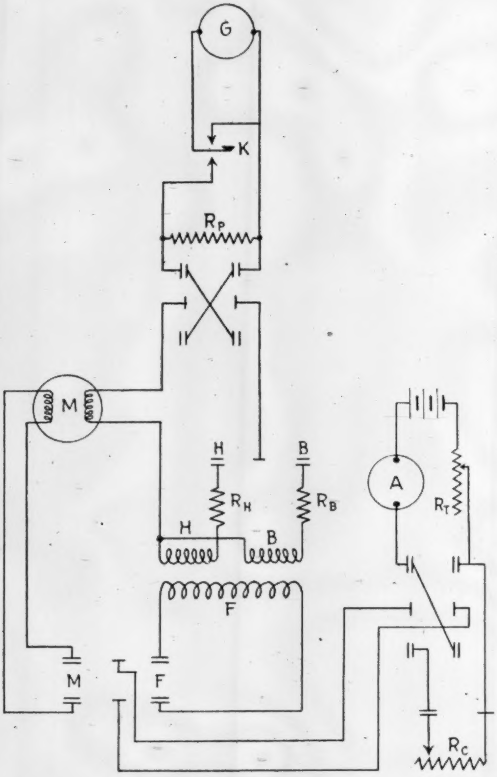

Fig. 2.—Diagram of Connections for Coercive Force Readings.

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[1] It is important to distinguish between the ideas conveyed by the words *precision* and *accuracy*. The word *precision* is used to denote the fineness of reading or the smallest unit in which a quantity is measured, while the word *accuracy* denotes the degree of freedom from error of a result.

was practically negligible in comparison with the coercive force of the rings.

A number of tests were made on rings which had received various heat treatments. A typical set of data is given in Table I.

These data show that the coercive force gives a good indication of the heat treatment. The first three groups show practically no hardening effect, but the difference in quenching temperature between groups Nos. 3 and 4 of 27° C. is accompanied by a 50 per cent increase in coercive force. Group No. 5, with a still higher quenching temperature, shows a further though less conspicuous increase.

TABLE I.—COERCIVE FORCE TESTS ON RINGS QUENCHED IN OIL.

Group.	Quenching Temperature.	Number.	$H_{max} = 200$.		
			B_m	B_r	H_c
1	732° C. (1350° F.)	1	13 900	5 740	23.7
		2	14 650	7 430	23.3
		3	14 050	6 990	23.7
		4	13 850	6 630	23.2
		5	14 280	7 080	23.4
		6	14 450	6 850	23.9
		Mean	14 190	6 790	23.5
2	760° C. (1400° F.)	1	14 000	6 780	23.8
		2	14 750	7 130	24.2
		3	13 900	6 520	23.2
		4	14 000	6 560	26.0
		5	13 900	6 700	24.2
		6	13 700	6 200	24.3
		Mean	14 040	6 650	24.3
	788° C. (1450° F.)	1	14 260	8 120	24.3
		2	13 680	6 440	25.2
		3	13 580	6 330	25.2
		4	13 680	6 500	25.7
		5	13 470	6 250	25.2
		6	13 400	6 240	25.3
		Mean	13 680	6 650	25.2
	815° C. (1500° F.)	1	12 430	6 410	38.6
		2	12 960	7 440	41.0
		3	12 400	6 600	38.4
		4	13 100	7 500	37.0
		5	12 320	6 960	40.5
		6	12 940	7 160	36.7
		Mean	12 590	7 010	38.7
5	843° C. (1550° F.)	1	13 140	8 140	43.2
		2	12 780	7 480	44.0
		3	12 300	7 040	44.8
		4	12 800	7 400	44.0
		5	12 290	6 870	44.5
		6	12 050	6 630	44.7
		Mean	12 560	7 260	44.2

It was noticed that group No. 4 gave the greatest variations in coercive force values and, in order to find out whether or not these variations were significant, the rings were tested for file hardness by an experienced mechanician who had no previous knowledge of the coercive force values. Table II gives the results of this test.

TABLE II.—TESTS OF RINGS IN GROUP NO. 4.

File Hardness.	Ring No.	Coercive Force.
1	2	41.0
2	5	40.5
3	1	38.6
4	3	38.4
5	4	37.0
6	6	36.7

It is significant that the order of hardness as determined by the two methods is identical, although the agreement in the case of rings Nos. 1 and 3 is probably accidental, as the difference in coercive force readings is less than the probable experimental error.

TABLE III.—MEAN VALUES FOR GROUPS 4 AND 5 AFTER SUCCESSIVE DRAWINGS.

Drawing Temperature, deg. cent.	Group 4.			Group 5.		
	B_m	B_r	H_c	B_m	B_r	H_c
Not drawn	12 590	7 010	38.7	12 560	7 260	44.2
100	13 330	8 280	36.2	13 460	8 550	39.7
150	13 400	8 200	34.6	13 570	8 550	37.3
200	13 620	8 350	33.5	13 810	8 550	37.3
250	14 060	8 520	33.3	14 560	8 860	34.4
300	14 770	8 330	28.6	14 960	8 320	29.2
350	14 820	8 490	28.9	15 140	8 370	29.5
400	14 820	8 240	28.1	15 360	9 130	27.9
Annealed 850	14 720	8 010	28.1	14 790	7 870	27.6

After the magnetic measurements had been made, groups Nos. 4 and 5 were drawn to successively higher temperatures and finally annealed. The results of the magnetic measurements are recorded in Table III.

It is of interest to note the relatively marked decrease in the coercive force values between 200 and 300° C., within which range the magnetic transformation of cementite (Fe_3C) takes place.

Although this method yields results which furnish a satisfactory basis for comparing the hardness of ball bearing races, it is open to a number of serious objections from the practical point of view. It requires the use of a sensitive ballistic galvanometer which is difficult to use under factory conditions, great care must be taken that the contact between the poles of the electromagnet and the rings is good (it may even be necessary to grind the contact surfaces to make them flat and smooth) and a comparatively long time is required for the test. Furthermore the detection of flaws, such as cracks and soft spots, is not possible by this method. A number of different plans were considered for overcoming these practical difficulties, but it was finally decided that an entirely different method gave greater promise of practical application. This other method consists of the measurement of rotary hysteresis.

ROTARY HYSTERESIS MEASUREMENTS.

The theory of the second method depends upon the fact that if a disk or ring of steel is placed in a rotating magnetic field, such as that produced by a rotating electromagnet, a torque is exerted upon it. This is due to the phenomenon of magnetic hysteresis. The resultant magnetic poles induced in the specimen lag by a certain angle behind the poles of the electromagnet as it rotates, and thus produce a torque which can be measured by means of a suitable spiral spring. The torque is proportional to the energy required to rotate the magnetization of the specimen through one revolution. If the speed is kept low, so that the effect of induced eddy currents is negligible, the torque is independent of the speed of rotation. The results of a number of experiments indicate that the value of torque due to rotary hysteresis may be taken as a criterion of mechanical hardness.

The same electromagnet used in the former experiments was mounted so that it could be revolved on ball bearings about a vertical axis. Direct current was supplied to the magnet by means of slip rings. The races were clamped on a self-centering holder at the end of a shaft mounted in ball bearings and supported from above. This shaft was also provided with a spiral spring and a pointer and scale for measuring the torque.

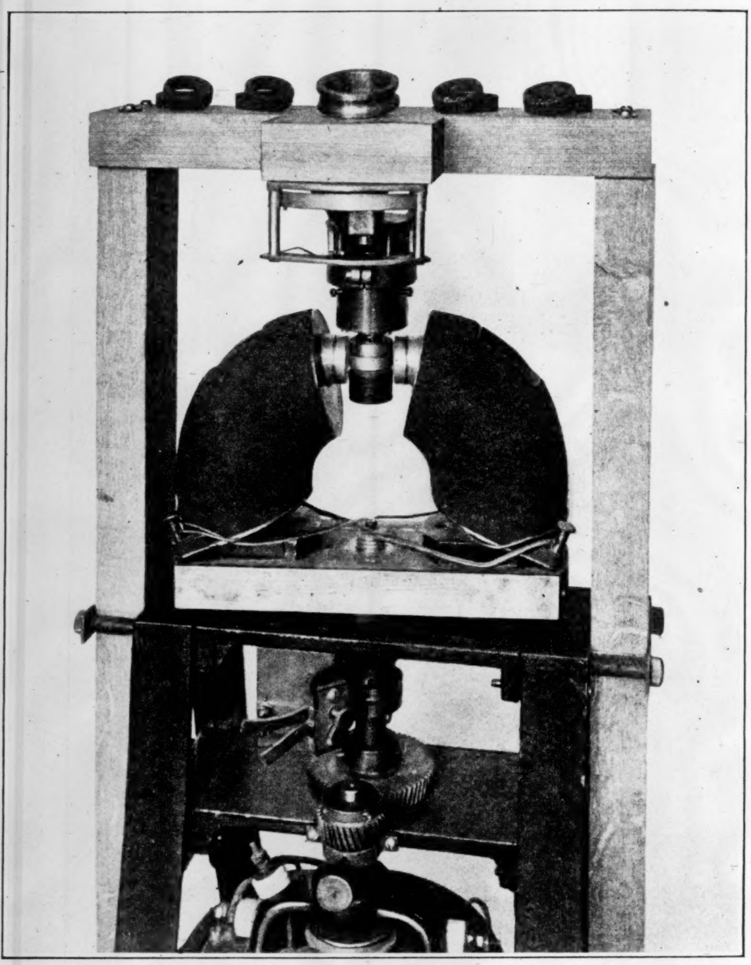

FIG. 3.—Apparatus for Rotary Hysteresis Measurements.

A reproduction of a photograph of the apparatus is given in Fig. 3.

A number of experiments were made to determine the induction in the rings with various values of current and various widths of air gap and as a result it was decided to make the final observations at a constant current of 2.5 amperes and a fixed gap of approximately 3 mm. The result of this procedure is that the induction in soft rings is somewhat higher than that in the hard rings, but since the energy loss in the hard rings is very much greater than in the soft ones the difference in induction is not important from the point of view of a practical test. The speed of rotation was approximately 100 to 200 revolutions per minute.

TABLE IV.—TORQUE TESTS ON RINGS QUENCHED IN OIL.

Group No.	Quenching Temperature.	Torque Reading.
1................	732° C. (1350° F)	72
2................	760° C. (1400° F)	113
3................	788° C. (1450° F)	121
4................	815° C. (1500° F)	123
5................	843° C. (1550° F)	123

NOTE.—There were six rings in each group and the average reading is recorded.

TABLE V.—FURTHER TORQUE TESTS.

Group.	Quenching Temperature.	Torque Reading.[1]
1................	732° C. (1350° F.)	35
2................	760° C. (1400° F.)	68
3................	788° C. (1450° F.)	69
4................	815° C. (1500° F.)	73
5................	843° C. (1550° F.)	66

[1] Average for the group.

A number of measurements were made on several groups of rings quenched in oil from different temperatures. A typical set of results is given in Table IV.

Observations were also made on the effect of drawing the quenched rings to various temperatures. The results were entirely similar to those obtained from readings of coercive force, showing a sharp drop of about 50 per cent in the readings between drawing temperatures of 200 and 300° C.

In view of the fact that the ultimate criterion of the practical usefulness of this method will be the result of tests at the shop, in connection with other physical tests or the performance of the product, little work has been done in the laboratory in the way of correlating the readings with anything other than heat treatment. If the apparatus indicates sufficiently small differences in heat treatment, further development in a commercial way would seem to be warranted. The results given in Table V are of interest in this connection.

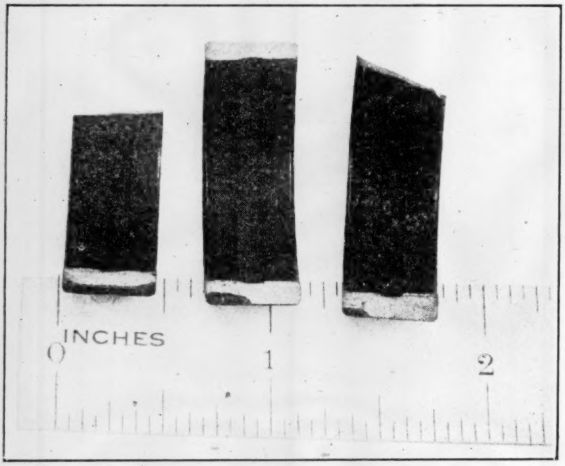

FIG. 4.—Quenching Cracks Detected by Rotary Hysteresis Apparatus.

It will be noted that the reading for group No. 5, though it should give the highest reading of all, is lower than for any other group except group No. 1, which in fact was not hardened. The reason for this apparent inconsistency was discovered by an examination of the records of the heat treating, which disclosed the fact that group No. 5 was overheated 50° F. and then allowed to cool until the rings were 100° F. below the desired temperature before they were reheated. This treatment apparently decarbonized the outer surface to some extent and probably accounts for the low reading. It is evident that this method gives a good indication of heat treatment.

If a ring has soft spots or cracks in it, the torque varies through wide limits during each revolution, as indicated by oscillations of the pointer. This affords a means for the detection of flaws in the rings. A number of such rings were encountered in the course of the tests. Generally there was no visible indication of a flaw, but upon breaking the rings with a hammer blow, rust marks were discovered in every case indicating the presence of cracks. Fig. 4 shows several cracked rings that were detected in this way.

Early in the course of the investigation the possibility of producing a rotating magnetic field by means of a polyphase electromagnet was suggested. Such an arrangement would have the great advantage of requiring no rapidly moving parts. A three-phase electromagnet was constructed and tried out. Although the apparatus gave results in substantial agreement with the rotating direct-current electromagnet, it has the disadvantage that it does not subject all parts of a ring to the same magnetic influence; and furthermore, because of the high speed of rotation of the magnetic field, it does not indicate the presence of flaws. For these reasons the rotating electromagnet seems to be preferable and a design is being prepared for a rotating electromagnet apparatus suitable for operation under shop conditions and which offers reasonable promise of success.

SUMMARY.

In conclusion, the results of the investigation of which this paper constitutes a progress report indicate:

1. That the magnetic properties and in particular the coercive force and rotary hysteresis constitute good criteria of the degree of hardness of a ball bearing race;
2. That the coercive force and rotary hysteresis values are sensitive to the influence of slight variations in heat treatment;
3. That by means of rotary hysteresis measurements it is possible to detect flaws;
4. That the application of magnetic analysis to the inspection of ball bearing races has commercial possibilities.

LOCATION OF FLAWS IN RIFLE BARREL STEEL BY MAGNETIC ANALYSIS.

By R. L. Sanford and Wm. B. Kouwenhoven.

SUMMARY.

This paper describes an investigation which was undertaken for the purpose of determining whether an application of magnetic analysis was practicable for the detection of flaws in rifle barrel steel. By means of apparatus especially constructed for the purpose a large number of bars were explored for magnetic uniformity along their length. In spite of the fact that these bars were taken from material which had previously been rejected as the result of drilling tests, not one was found which contained a pipe. The results obtained, however, demonstrated that the method is amply sensitive to detect and locate flaws. Further study is necessary to determine to what degree the sensitiveness of the apparatus should be reduced in order not to cause the rejection of material which is satisfactory for all practical purposes, and also to determine the type and magnitude of the effect which will be produced by a pipe. For this reason the work is being continued by the Winchester Repeating Arms Co., who cooperated in the investigation and at whose plant the apparatus has been installed.

LOCATION OF FLAWS IN RIFLE BARREL STEEL BY MAGNETIC ANALYSIS.

By R. L. Sanford and Wm. B. Kouwenhoven.

Introduction.

One of the practical applications of magnetic analysis consists of the detection of flaws in bar stock used in the manufacture of steel products. At the request of the Ordnance Department of the Army and the Winchester Repeating Arms Co., an investigation was undertaken during the war with the end in view of applying this method of magnetic analysis to the testing of rifle steel.

In view of the fact that flaws, generally consisting of pipes or slag inclusions, interfere with the drilling of the barrels or may possibly affect their strength, it was considered that a non-destructive test which would detect and locate such flaws before further work had been done on the barrels would prove to be of great value. Such a method of inspection would make possible not only the rejection of faulty material, but also the acceptance of all the satisfactory bars in a given shipment and thus effect a great saving both of material and labor. It is the object of this paper to describe the apparatus used in the investigation and to present the results thus far obtained.

Theory.

The method employed was that of the determination of the degree of magnetic uniformity along the length of the bars, based upon the theory that if a bar is uniform magnetically along its length, it is also uniform mechanically. A number of barrel forgings were first tested by "point by point" method originally used for the examination of bars intended for magnetic standards and which has already been described.[1] Fig 1 shows a specimen curve obtained by this method and Fig. 2 is a photograph showing the flaw which was indicated by this curve.

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[1] Sanford, "The Determination of the Degree of Uniformity of Bars for Magnetic Standards," *Scientific Paper No. 295*, U. S. Bureau of Standards.

Since this method is not adapted to the examination of very long bars, and is too time-consuming for a commercial test, it was decided to use a somewhat different method, substantially similar to that used by Burrows[1] for the examination of steel rails. In this method the magnetizing force is applied by means of a solenoid which surrounds the bar and travels along its length. Mounted within this magnetizing solenoid is a test

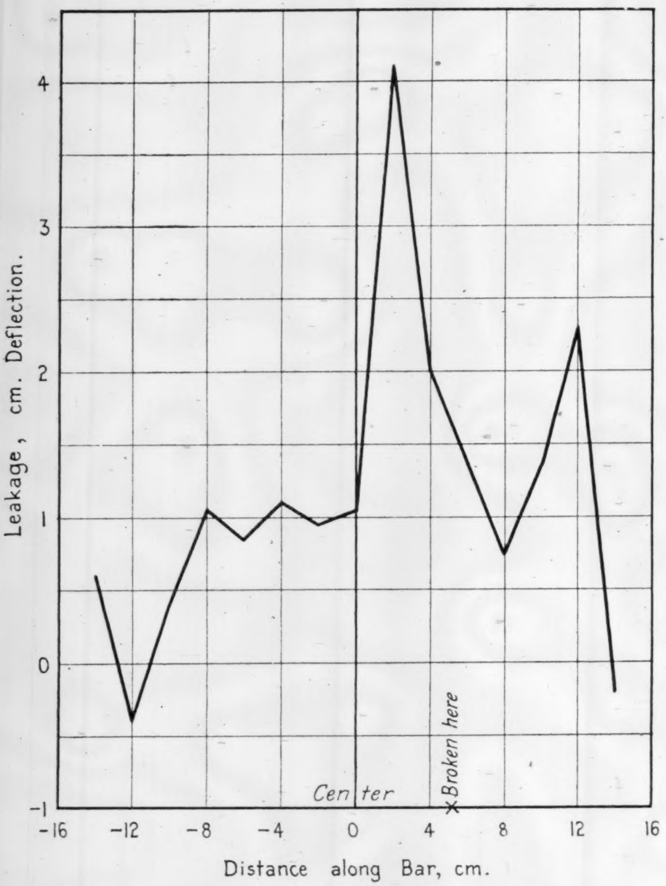

FIG. 1.—Magnetic Uniformity Curve. Piped Sample.

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[1] Burrows, "Correlation of the Magnetic and Mechanical Properties of Steel," *Scientific Paper No. 272*, p. 203, U. S. Bureau of Standards.

coil by means of which variations in magnetic flux within the bar can be measured. If the bar is magnetically uniform along its length its permeability is constant for a given magnetizing force and the magnetic flux at each point as the solenoid is moving along is constant. If this is the case, there will be no electro-motive force induced in the test coil as the solenoid travels the length of the bar. If, on the other hand, the permeability is not constant, the flux will vary and a corresponding electromotive force will be induced in the test coil which, if the coils are moved at a constant speed along the bar, is proportional to the change in flux. If, instead of using a single test coil, in the manner just described, we use two test coils connected in series opposition we obtain a result that is practically not affected by slight variations in the magnetizing current during a run, as any variations in flux linked with one coil is neutralized by corresponding changes in the other.

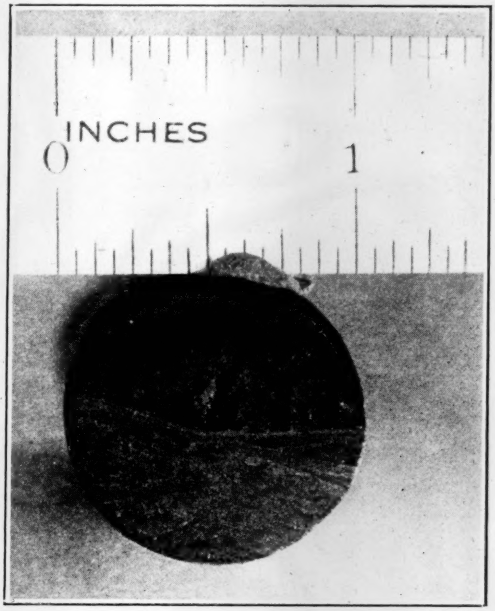

FIG. 2.—Photograph of the Flaw Indicated in the Curve of Fig. 1.

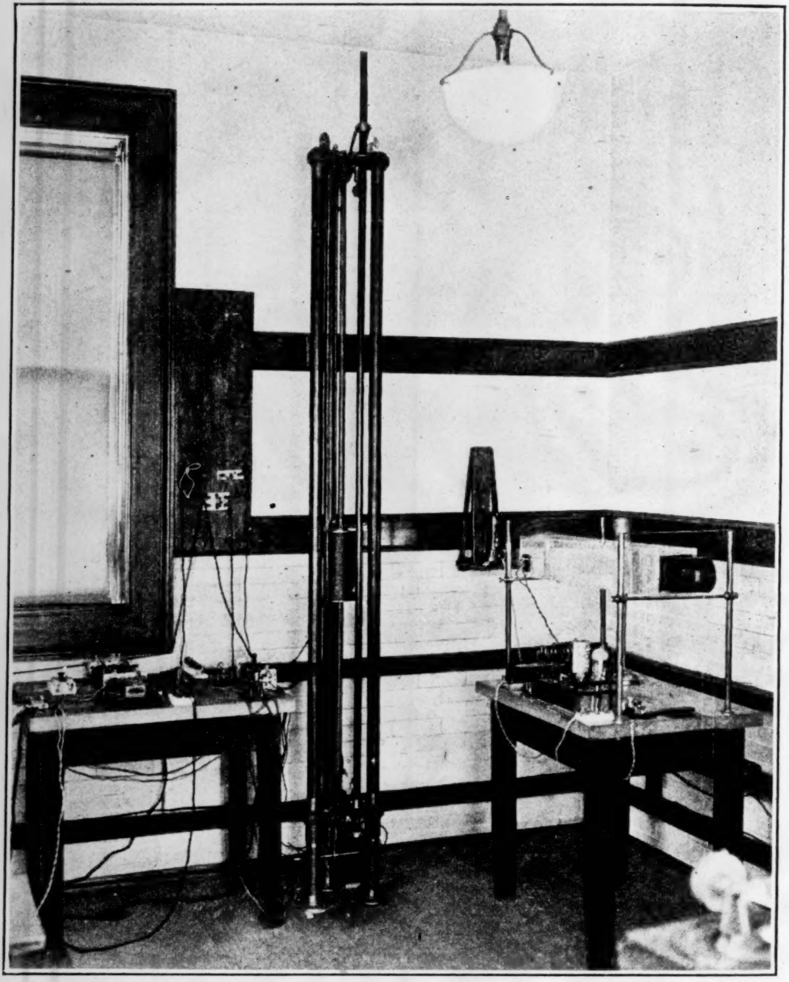

FIG. 3.—Apparatus Assembled at the Bureau of Standards.

DESCRIPTION OF APPARATUS AND PROCEDURE.

Fig. 3 is a photograph of the apparatus as set up at the Bureau of Standards for preliminary experiments before it was taken to the Winchester Plant at New Haven for test under factory conditions. The bar to be examined is clamped at the centers of two triangular end plates of cast iron. These end plates are supported by three wrought-iron pipes which also constitute the return circuit for the magnetic flux induced in the test bar. The magnetizing solenoid, which is shown in more detail in Fig. 4, is supported between the pipes by means of cords running over pulleys and carrying counterweights which hang inside the supporting pipes. One of these cords is continuous and runs over a drum mounted on the shaft of a small

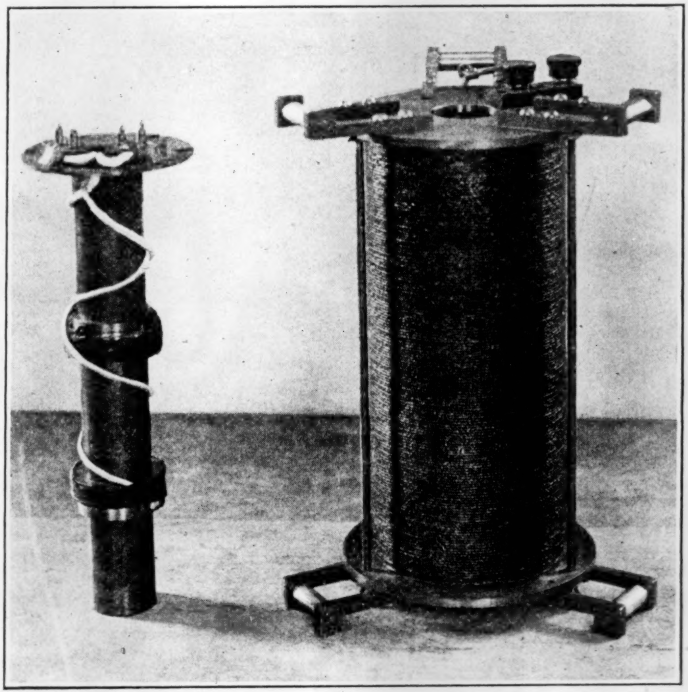

FIG. 4.—Magnetizing Solenoid and Test Coils.

electric motor. By means of this arrangement the coils can be run up and down along the length of the bar. Magnetizing current is supplied to the solenoid by means of a storage battery and regulated by means of sliding rheostats. The guiding rollers shown in Fig. 4 were later arranged to bear on the test bar instead of on the iron pipes as it was found that many of the bars were not straight. The test coils are mounted on a separate tube and their position is adjustable. These test coils have 500 turns each, and are connected through suitable resistances

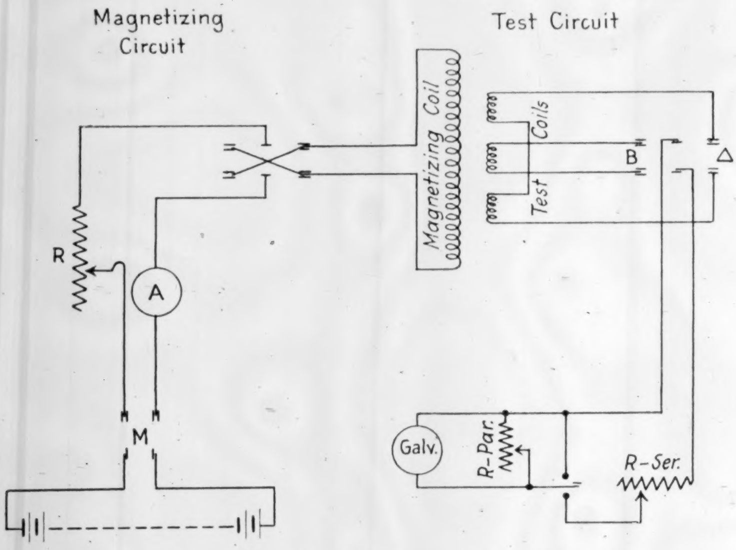

FIG. 5.—Diagram of Electrical Connections.

to the galvanometer shown at the right of the apparatus in the photograph. Deflections of the galvanometer are observed by means of a spot of light reflected from its mirror on to a ground glass scale. Permanent records of these deflections are made by means of a photographic arrangement which consists of a long light-tight box upon one end of which is mounted an ordinary oscillograph drum which carries the photographic film. This drum is rotated at the proper speed by means of a belt connected to the driving motor of the apparatus. By means of contacts located at one-foot intervals on the driving cord, a light is flashed inside the box which makes a record on the film for each foot of travel and thus affords a means for locating the position on the bar of any observed non-uniformity. A diagram of the electrical connections is given in Fig. 5.

When a photographic record indicating the magnetic uniformity of a bar is to be made, the procedure is as follows: The bar is clamped in the apparatus, the galvanometer circuit is then closed and the drum carrying the photographic film is given one complete revolution. The spot of light reflected from the galvanometer mirror thereby traces a straight line which serves as the reference axis. The switch M is then closed and the magnetizing current is adjusted to the proper value by means of the regulating rheostat R. With the galvanometer connected

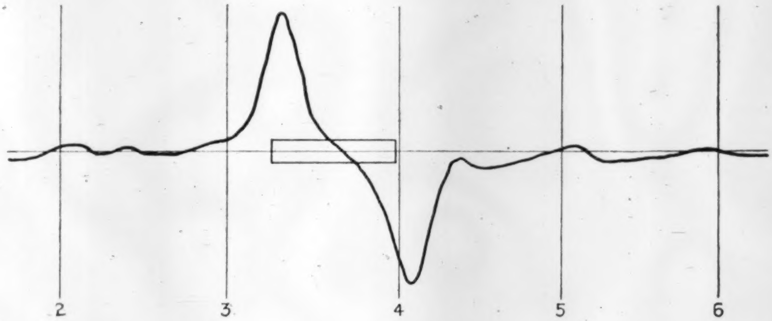

FIG. 6.—Record with Single Test Coil.

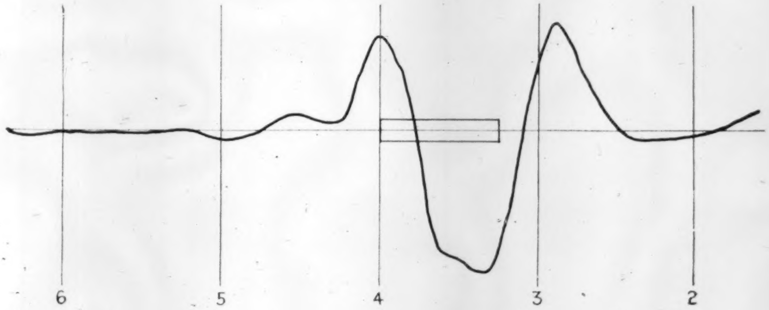

FIG. 7.—Record with Differential Test Coils.

either to the single test coil or the differential coils as desired, the driving motor is then started and the coil is run the length of the specimen with the film holder rotating at a uniform speed. Most of the records have been made by running the coils in one direction with the galvanometer connected to the single test coil, and in the other direction with the galvanometer connected to the differential coils. Fig. 6 shows a record taken by the use of the single coil and Fig. 7 shows the corresponding record taken with the differential coils. A rectangle is drawn on each of these records to show the position and extent of a strip of transformer iron which was attached to the bar in order to give the effect of a flaw.

PRELIMINARY STUDY AND ADJUSTMENT.

After the apparatus was completed and set up in the laboratory, it was necessary to consider a number of points in connection with its operation and to decide upon the proper adjustment of the test coils. The points to be considered included the proper flux density (B) in the specimen, the proper speed for the moving coils, the period of the galvanometer and, as just mentioned, the best location of the test coils. As a result of observations taken under a great variety of conditions, it was found that a flux density of approximately 15,000 gausses gives the best results. The speed of travel finally adopted was approximately half a foot a second. It is necessary, in order to insure that the record gives a true indication of the condition of the specimens, that the galvanometer have a fairly short period. If the period is too long, the galvanometer does not follow closely the changes in the induced electromotive force. A period of approximately one second was found to be satisfactory. The photograph of the test coils shows only two coils in position. For convenience, however, a third coil was made, and the differential coils were located 10 cm. apart and equidistant from the single coil, which was located at the middle of the magnetizing solenoid. With this symmetrical arrangement, records could be duplicated by running the coils in either direction.

A preliminary exploration to determine the flux distribution along the specimen for different positions of the magnetizing solenoid was made by a "point by point" method, using the single test coil connected to a ballistic galvanometer. Readings were taken upon reversal of the magnetizing current. The result of this exploration showed that, for a given magnetizing current, the flux is constant at different points along a uniform bar except for the regions very near the ends.

In order to study the effect of flaws varying in extent and kind, a number of records were made on a bar previously found to be uniform, to which were attached strips of transformer steel of various shapes and sizes. This procedure was necessary because of the difficulty of producing longitudinal flaws by artificial means. Fig. 8 shows the shapes and dimensions of the strips thus used. Figs. 9 to 12 inclusive are records obtained in this way. The location and shape of the added strip is indicated in each case upon the record. The figures show records taken both by means of the single test coil and by means of the differential coils. Figs. 13 and 14 show the effect of various treatments on a bar originally uniform. The treatments given, and

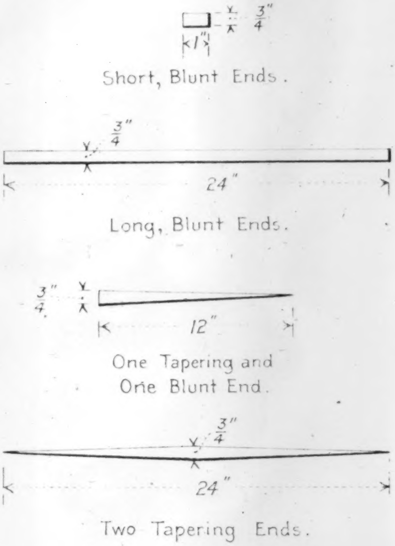

FIG. 8.—Dimensions of Added Strips.

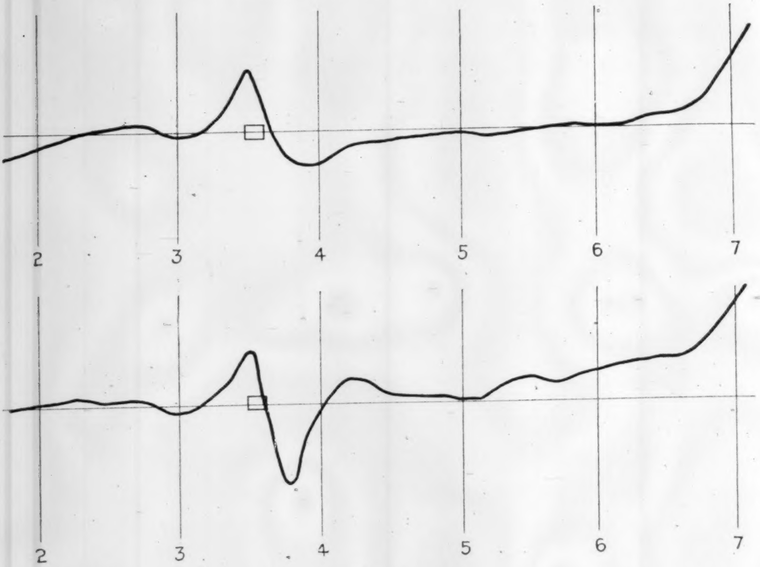

FIG. 9.

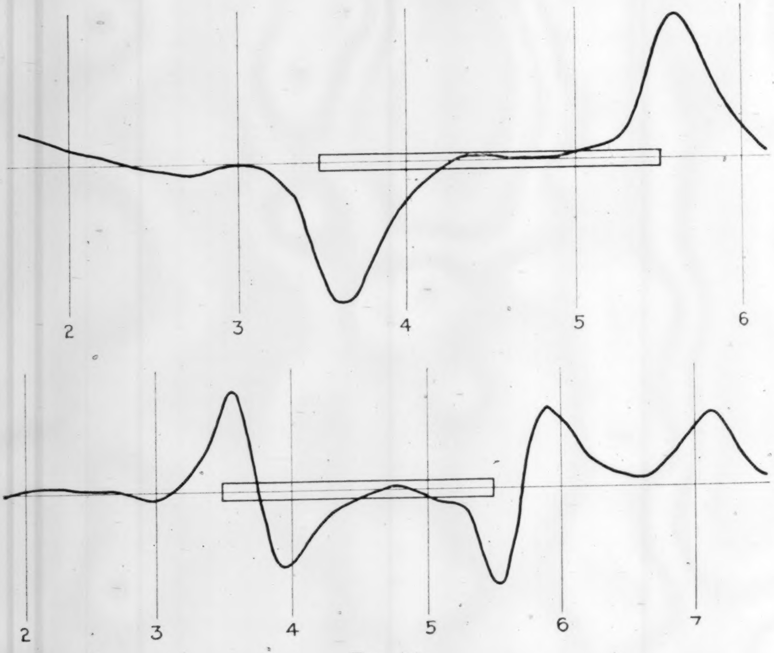

FIG. 10.

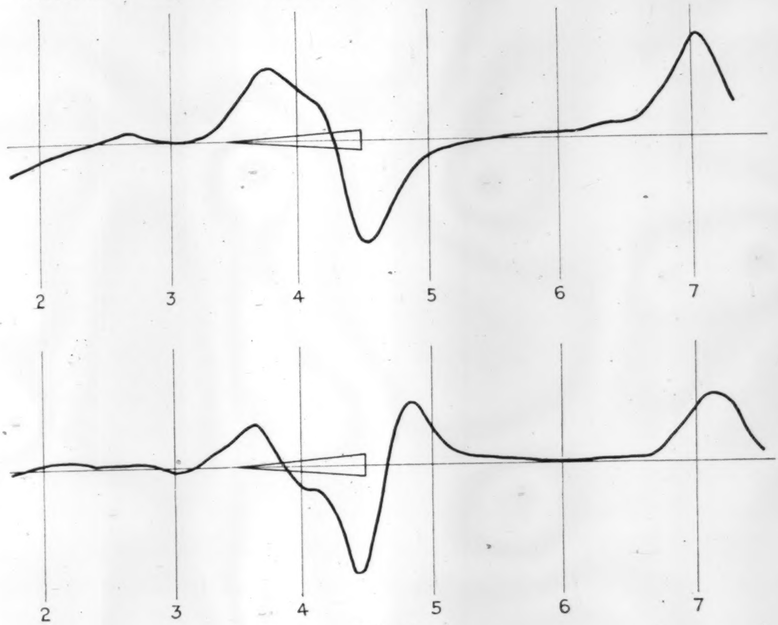

FIG. 11.

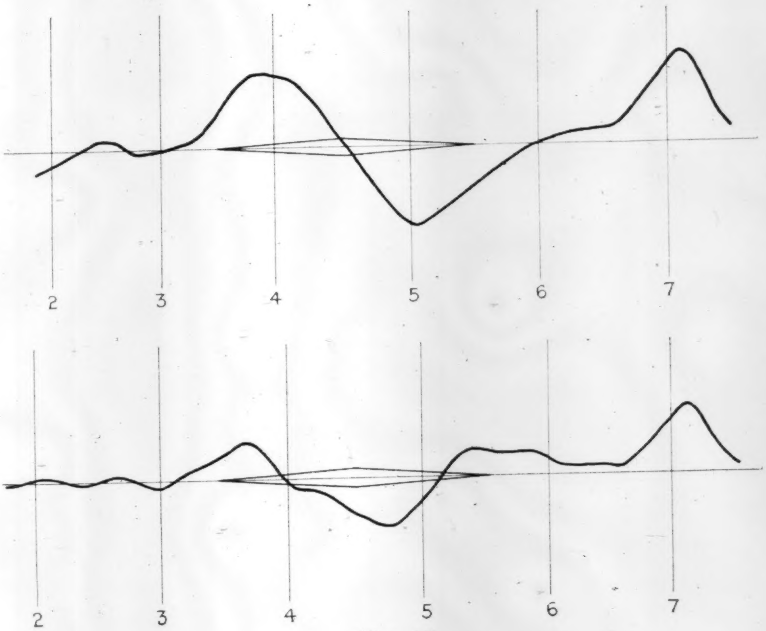

FIG. 12.

the locations, are indicated in the figures. It was at first feared that, due to the sensitiveness of the method, spurious indications would be obtained for bars which had been slightly bent during shipment and handling at the factory. The result of this last test, however, indicates that such is not the case.

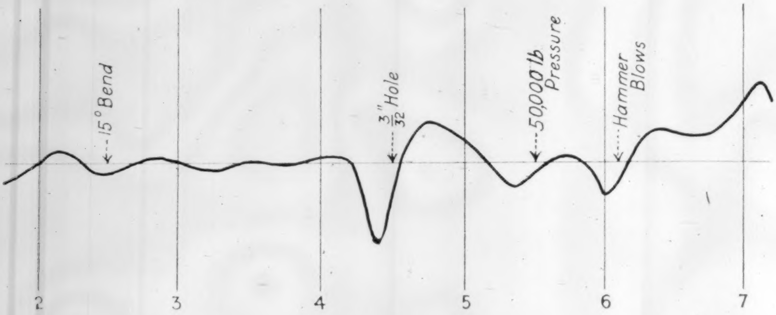

FIG. 13.

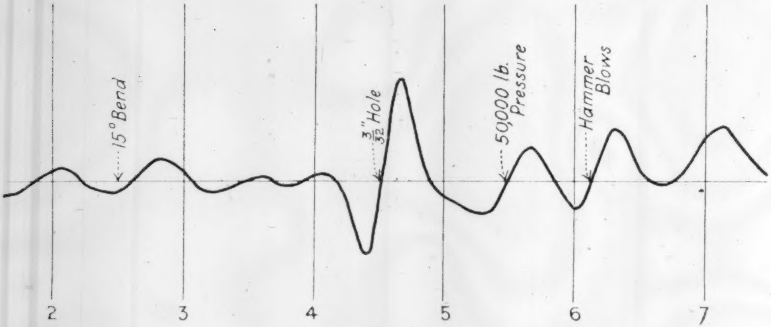

FIG. 14.

After the preliminary experiments just described, the apparatus was shipped to the plant of the Winchester Repeating Arms Co. at New Haven and there set up for final trial.

EXPERIMENTAL RESULTS.

The greatest difficulty in this line of investigation lies in the interpretation of the results. This is due to the fact that there are many causes which may produce magnetic inhomogeneity and it is difficult to differentiate between them. The work at New Haven was done with the end in view of obtaining data which would establish the amount of variation and the type of curve which accompanies a pipe. The procedure was to make records of bars which in a preliminary test showed large variations. These bars were chosen from lots of steel which had previously been rejected as the result of tests in the drilling shop. It is an interesting fact that even though this lot of steel had previously been rejected on account of pipes, not a single pipe was discovered in the drilling test on samples for which records of the magnetic uniformity had been obtained. This is true of all the steel examined up to March 31, 1919.

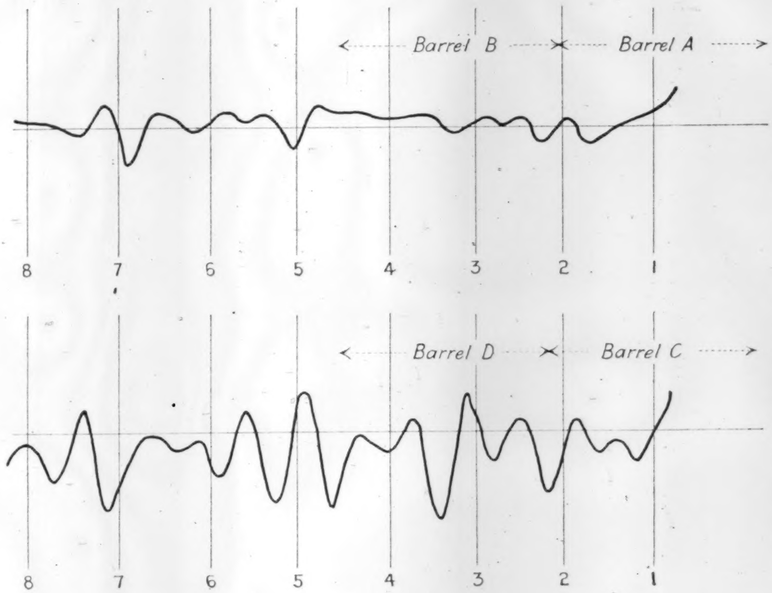

FIG. 15.

Figs. 15 and 16 show records of the degree of magnetic homogeneity of four bars of steel. These records were made with the differential test coils and with a fairly low sensitivity of the galvanometer. The portions of these bars from which barrel lengths were cut are indicated in the figure. Barrels A, B, C and D, cut from bars Nos. 1 and 9, and those cut from the entire length of bars Nos. 2 and 4, were sent to the shop for drilling tests. Barrels B and D gave trouble in drilling and each destroyed the edge of a drill, thus necessitating the use of a new drill to finish the bore. None of the other barrels gave trouble and the inside surfaces of all were smooth and bright. In view of the fact that additional data are necessary in order to draw satisfactory conclusions the Winchester Repeating Arms Co. is continuing the investigation.

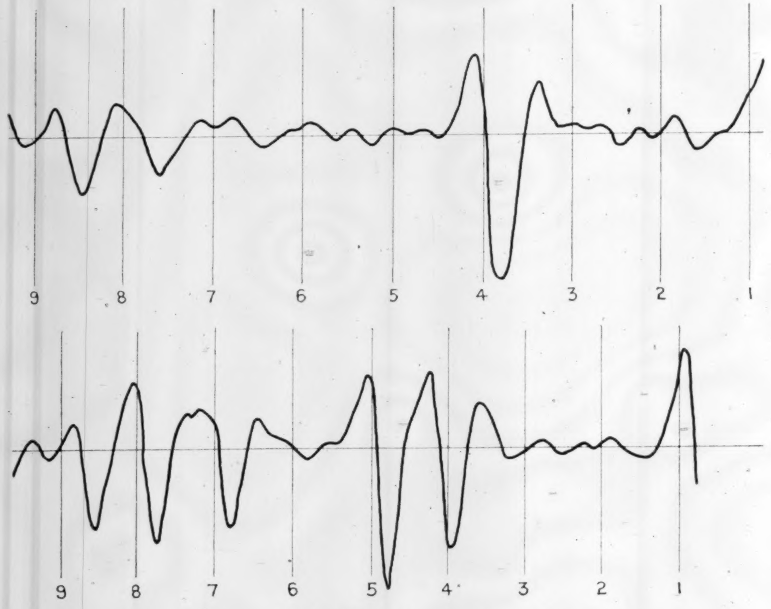

FIG. 16.

The authors wish to take this opportunity to acknowledge their indebtedness to Mr. J. S. Gravely, Mr. M. F. Fischer and Mr. J. S. Becker for their valuable assistance in carrying out this investigation.

CERTAIN ASPECTS OF MAGNETIC ANALYSIS.

By C. Nusbaum.

SUMMARY.

A new method of investigation for the determination of the metallographic structure of a steel is indicated; also a new method for the correlation of the magnetic and the mechanical properties of such material is outlined.

The essential points of the paper may be briefly summarized as follows:

1. That the magnetic properties of a steel are indicative of the transformations which it undergoes with heat treatment.
2. That such properties furnish suitable criteria from which the metallographic structure of such material may be inferred.
3. That no simple relationship exists between the magnetic and other physical properties of a steel product.
4. That by using "limiting values" of suitably chosen magnetic constants the mechanical properties of such a material are uniquely defined.

CERTAIN ASPECTS OF MAGNETIC ANALYSIS.

By C. Nusbaum.

Introduction.

This paper is presented primarily for the purpose of outlining certain definite methods of investigation in the field of Magnetic Analysis which it is believed will ultimately prove to be of considerable value in the correlation of the magnetic with other physical properties of steel as indicative of its behavior under service conditions.

For the purpose of this discussion magnetic analysis may be considered as divided into four distinct phases:

1. The detection by magnetic methods of inhomogeneities or non-uniformities in raw material and finished steel products.
2. The detection by magnetic methods of physical and chemical transformations which take place in iron and steel on heating or cooling.
3. The establishing of magnetic criteria for inferring the physical constitution of carbon and alloy steels as a result of a thorough study of their magnetic properties as related to their metallographic structure.
4. The establishing of general though definite relationships between the magnetic and the mechanical properties of these alloys. If such general relationships can be established, then the task of predicting the mechanical performance of a steel product from its magnetic properties will be rendered comparatively simple and not impossible of accomplishment as it seems at the present time.

Investigations on the detection of inhomogeneities or non-uniformities are represented by the experimental investigations of Burrows[1] and Sanford[2] and by papers presented at the present meeting of this Society. The detection of transformations on heating or cooling is well illustrated by the extensive experimental work of Honda[3] and his staff of investigators, and certain phases of their work will be discussed briefly. The major portion of this paper, however, will be devoted to a discussion of a magnetic method for the determination of the metallographic structure of steels and the prediction of their mechanical properties by means of a method of "limiting values" of the magnetic quantities.

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[1] Burrows, *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 87 (1917).

[2] Sanford, *Scientific Paper No. 295*, U. S. Bureau of Standards.

[3] Contributions, Tohoku University, Scientific Reports, Vols. 1–7, 1911–18.

DETECTION OF TRANSFORMATIONS.

Within recent years Honda[1] has used a magnetic method for detecting the change of structure of a substance. It consists in observing the abrupt change of the intensity of magnetization or of the magnetic susceptibility during the heating or the cooling of the substance. To this method of investigation he applies the term "Magnetic Analysis." It is based on the following experimental facts:

"1. The intensity of magnetization of simple homogeneous ferromagnetic substances decreases at first slowly and subsequently more rapidly (at high fields) as the temperature increases. At the critical temperature the magnetization vanishes.

"2. The critical temperature of a ferromagnetic element or compound is a characteristic constant for the substance and is independent of its external conditions.

"3. If a substance undergoes an allotropic transformation at a given temperature, the magnetization or the magnetic susceptibility is abruptly changed."

By means of this method of investigation Honda has performed very valuable experimental work on the various transformations of different kinds of steels, determining not only the critical temperatures of the various transformations but in some cases their nature as well. His investigations extend not only over the usual transformations generally designated by the symbols A_1, A_2, and A_3, but also over the magnetic transformation of cementite which he represents by the symbol A_0. The magnetic investigation of the physical transformations in steels is not accompanied by any time lag as in the usual investigations by thermal analysis, and is more convenient. This method of investigation thus becomes not only an additional but a valuable instrument of research for the metallographer.

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[1] Kotaro Honda, *Journal*, Iron and Steel Inst., September, 1918.

The results for the A_1 transformation obtained by Honda[1] on a specimen of 0.64-per-cent carbon steel are reproduced in Fig. 1. The measurements were taken with a magnetometer and in the graph the ordinates (δ) are proportional to the intensity of magnetization. As the specimen is heated at a normal rate the magnetization decreases in value at higher temperatures until it vanishes in the neighborhood of 780° C. On cooling the specimen (at a normal rate) the magnetization again appears but at a lower value of the temperature. This temperature-displacement is a result of the inertia of the transformations, for when the heating and cooling are allowed to take place over a longer time interval (1 hr. 31 min., and 2 hr. 30 min., respectively) the transformations are less displaced and take place at practically constant values of the temperature. The decrease in the magnetization at 215° C. on heating (or increase on cooling) is due to the magnetic transformation of cementite.

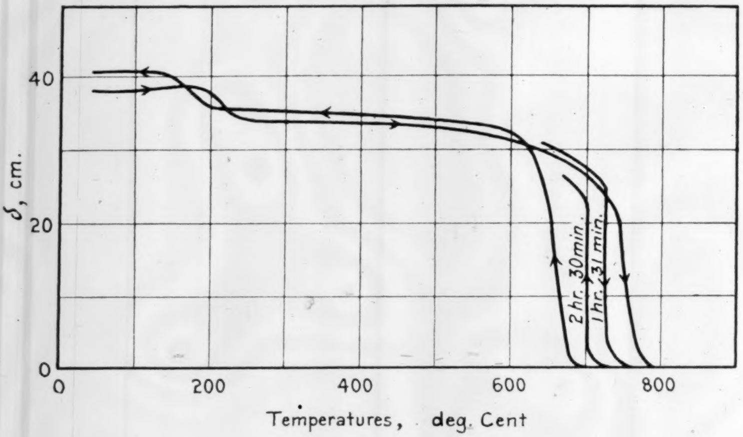

FIG. 1.—The A_1 Transformation of a 0.64-per-cent Carbon Steel (Honda).

Fig. 2[2] shows the transformations, detected magnetically, at the A_3 point in a specimen of almost pure iron. The magnetic susceptibility (x) is determined by means of a magnetic torsion balance. The temperature displacement of the transformation on heating and cooling is again clearly indicated.

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[1] Honda, Scientific Reports, Tohoku University, Vol. 5, pp. 285–295 (1916).

[2] Honda and Takagi, Scientific Reports, Tohoku University, Vol. 4, pp. 261–269 (1915).

Since the thermo-magnetic transformation of cementite can not be detected by the usual methods of thermal analysis but only by the magnetic method, this transformation will be discussed more fully than the others mentioned above. It was

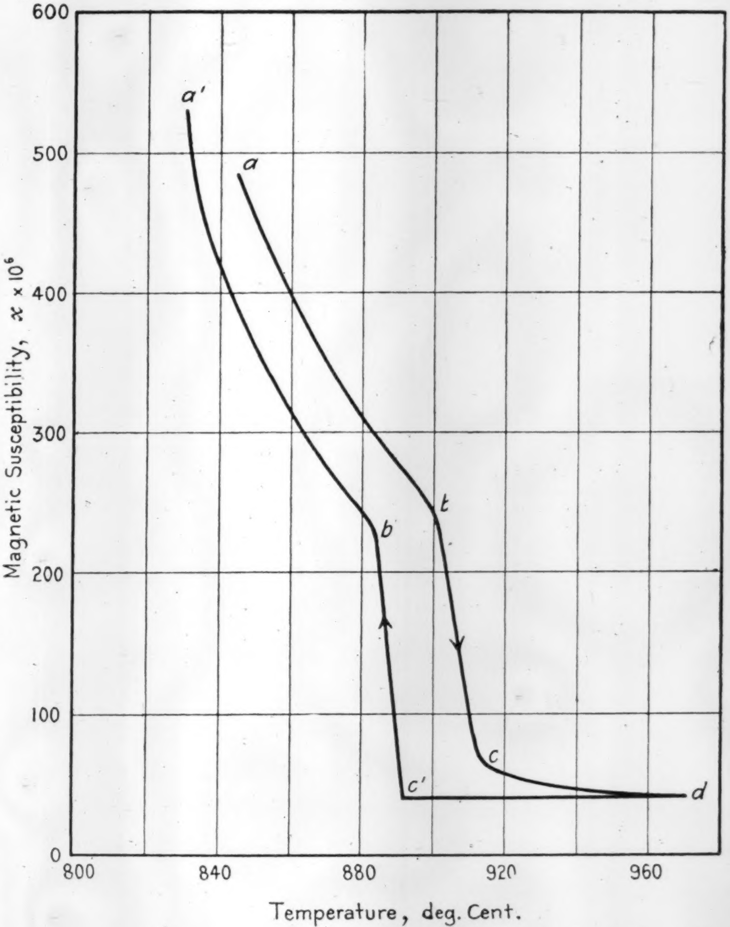

FIG. 2.—The A_3 Transformation of a Specimen of Pure Iron (Honda).

first observed by Wologdine[1] in a specimen of pure cementite, and by Maurain[2] in an 0.85-per-cent carbon steel. Experiments by S. W. J. Smith[3] verified these observations. Within recent years Honda and Murakami[4] have conducted extensive experiments on the transformation of cementite and of the double carbide of tungsten. The specimens were obtained from a series of carbon and tungsten steels by electrolysis.

Only the transformation of the cementite[5] will be discussed here. The specimen, compressed into a highly compact form, is heated in a vacuum to successively higher temperatures. During the heating and cooling the values of the intensity of magnetization are observed at different temperatures. Curve 1 of Fig. 3 clearly indicates the total disappearance of the magnetization of a specimen of cementite at 215° C. Curve 2 shows that in heating the specimen to 400° C. no appreciable decomposition takes place. In curves 3 and 4 a slight increase of magnetization above the critical point is observable, showing that by heating the specimen to 400° or 700° a small partial decomposition has occurred, and iron is set free. In curves 5 and 6 the specimen was respectively heated to 800° and 900° C. and then cooled; these curves show a characteristic change for the eutectic transformations above and below 700° and a decided decrease of the A_0 transformation. This shows that a considerable amount of the cementite is already decomposed, giving rise to free iron, and this iron forms an eutectic mixture with a portion of the undecomposed cementite. In curve 8 the specimen was heated to 980° and then cooled; the general form of the curves is similar to that of carbon steel containing about 0.5-per-cent of carbon. It is therefore highly probable that over 90 per cent of the cementite has been decomposed.

DETERMINATION OF THE METALLOGRAPHIC STRUCTURE.

In many of the earlier experiments on the magnetic properties of the various magnetic metals and some of their alloys, very little attention was given either to the purity of the materials or to their structural condition as depending on their previous treatment. It is only within the last fifteen years that the rôle which the various components of an alloy steel perform in the variation of its magnetic as well as its mechanical properties has been fully appreciated. Perhaps the foremost

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[1] Wologdine, *Comptes Rendus*, Vol. 148, p. 777 (1909).

[2] Maurain, Ann. de Chim. et de Phys. Vol. 20, p. 353 (1910).

[3] Smith, *Proceedings*, Physical Society of London, Vol. 24, p. 62 (1911); also Vol. 25, p. 77 (1912).

[4] Honda and Murakami, Scientific Reports, Tohoku University, Vol. 6, p. 23 (1917).

[5] Honda, *Journal*, Iron and Steel Inst., September, 1918.

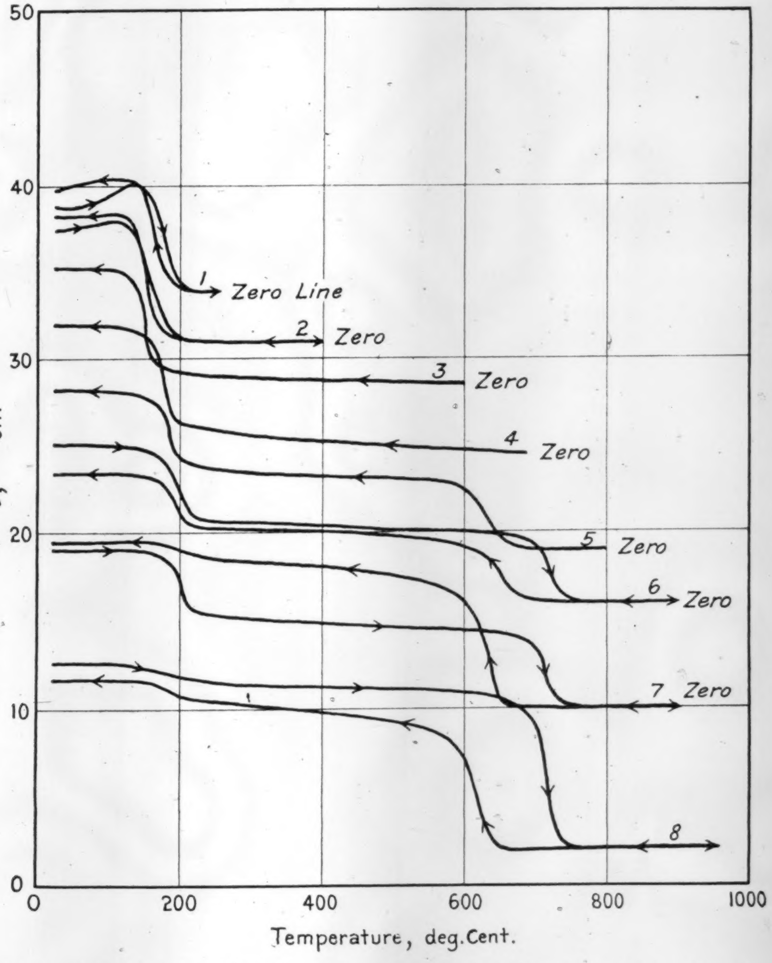

FIG. 3.—The Magnetic Transformation of Cementite (Honda and Murakami).

experimental work along this line is that of Hadfield and Hopkinson[1] on manganese steels, Yensen[2] on silicon steels, Burgess and Aston[3] and also Mathews[4] on various magnetic alloys. Although in these experiments the specimens received definite heat treatments, yet the range of heat treatments was in many cases entirely too limited to be of value in the field of magnetic analysis. Also in much of the scientific data available little attention has been given to the structural condition of the material, which makes the data of quite limited value from either the standpoint of practical application or of scientific accuracy.

The magnetic characteristics of a material are indicative of certain changes or transformations taking place within it during the process of heat treatment. Such transformations can be very well illustrated by a study of the magnetic characteristics[5] of a carbon steel of the following composition:

Carbon	1.04	per cent
Manganese	0.34	"
Phosphorus	0.047	"
Sulfur	0.038	"
Silicon	0.017	"

The specimen was quenched in water from a temperature of 800° C. and then drawn at 100° C. temperature intervals, until it was finally annealed. While in the quenched condition and after each drawing operation the normal induction curve and the hysteresis constants as well as the mechanical hardness were determined. Similar data were taken for a specimen of the same composition quenched in oil and subjected to a similar series of drawing operations. During each heating process the specimen was held at its maximum temperature for a period of a few minutes and then air cooled.

In Fig. 4 the magnetic and mechanical hardness data for these specimens under the two conditions of quenching and sub-

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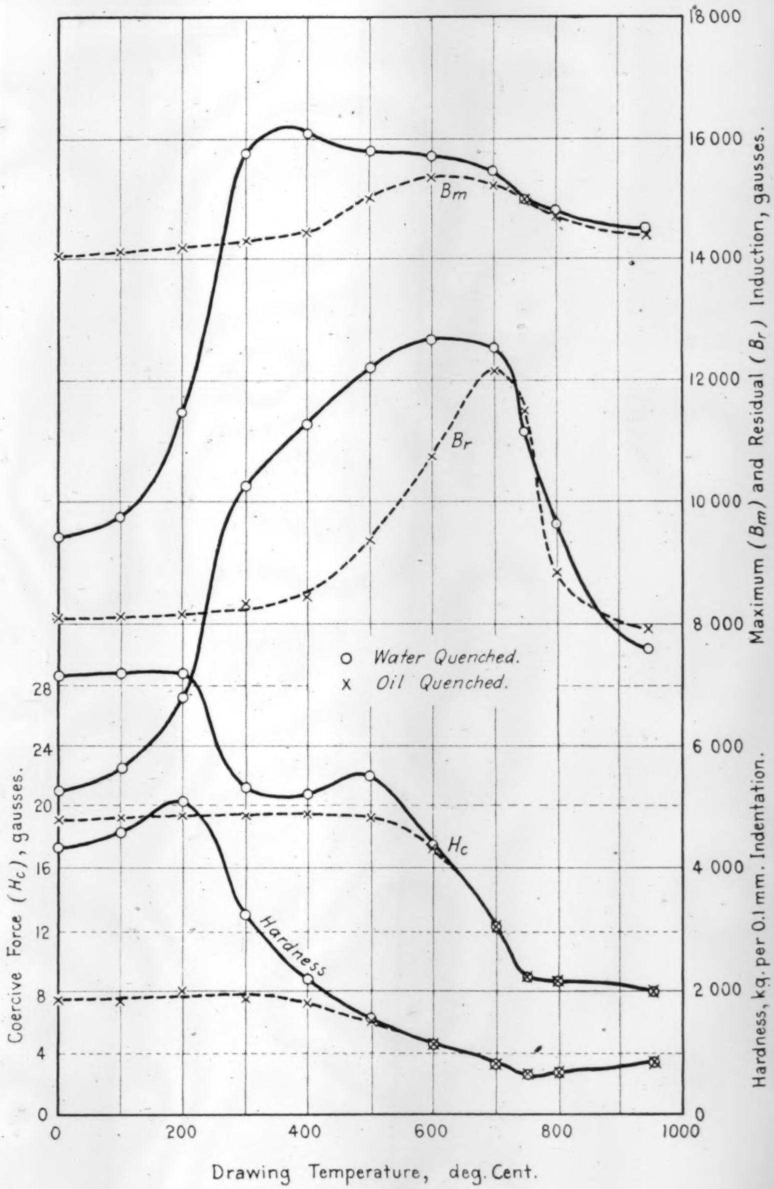
[1] Hadfield and Hopkinson, *Journal*, Iron and Steel Inst., Vol. 86, pp. 106–121 (1914).

[2] Yensen, *Proceedings*, Am. Inst. Elect. Engrs., Vol. 34, pp. 2455–2495.

[3] Burgess and Aston, *Metallurgical and Chemical Engineering*, Vol. 8, pp. 23–26 (1910); also pp. 79–81; and pp. 131–133.

[4] Mathews, "Magnetic Habits of Alloy Steels," *Proceedings*, Am. Soc. Test. Mats., Vol. XIV, Part II, p. 50 (1914).

[5] The data here presented were taken by Fahy and are presented by Burrows and Fahy in the paper "Magnetic Analysis as a Criterion of the Quality of Steel and Steel Products" at this meeting of the Society. See p. 5.—ED.



4.—Effect of Heat Treatment on the Maximum Induction (B_m), Residual Induction (B_r), Coercive Force (H_c) and the Mechanical Hardness of a 1-per-cent Carbon Steel.

sequent drawing are plotted against the drawing temperature as the independent variable. The graphs with the circles are for the water-quenched specimen and those with the crosses for the oil-quenched, respectively.

The mechanical hardness data are given in terms of kilograms per 0.1 mm. indentation.

When a carbon steel is heated to slightly above the upper critical range the γ iron forms a solid solution with the cementite. This solid solution is known as austenite. If the temperature interval above this upper range is small and the period during which the temperature is maintained is short, the steel under these conditions has its greatest refinement. This condition of physical refinement may be maintained at room temperatures if it is cooled very rapidly through the transformation range so as to arrest the transformations which would normally take place with slower cooling. The effect is increased in the case of alloy steels by the action of the alloying elements which retard the transformations to a greater or less extent. At very slow rates of cooling (such as furnace cooling) the γ iron changes to α iron, or ferrite, while the cementite is thrown out of solution and with a definite percentage of the ferrite forms pearlite. With intermediate rates of cooling from above the critical range intermediate transformations are obtained.

Martensite is generally believed to correspond to an early stage in the transformation of austenite in passing through the critical range. Opinions differ, however, as to its exact nature. It is most readily obtained through the quenching of small pieces of high carbon steel in cold water. While the structure of the given specimen (water-quenched) was not examined microscopically, yet the conditions of quenching are such as to indicate the existence of almost pure martensite.[1] That it is martensitic in structure is also indicated by the high values of the mechanical hardness.

Experiments by Honda[2] on the magnetic transformation of cementite in quenched carbon steels show clearly that the cementite forms a solid solution with the iron. As the specimen is successively heated to higher temperatures, an increasing amount of the cementite is precipitated from the solid solution. This precipitation is indicated by the increasing magnitude of the magnetic transformation of cementite.

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[1] Sauveur, "The Metallography and Heat Treatment of Iron and Steel," 2d edition, p. 284.

[2] Honda, Scientific Reports, Tohoku University, Vol. 6, p. 149 (1917).

If the cementite, which is one-tenth as magnetizable as iron, is dissolved in ferrite the intensity of magnetization of the latter is lessened according to Tammann's[1] law. As the cementite is set free the magnetization of the iron is restored. The end of this transformation is indicated by the maximum value of the B_m curve in the neighborhood of 400° C. This temperature marks the completion of the transition from martensite to troostite and the specimen is in a tempered condition. This transition is also indicated by lower values of both the coercive force and the mechanical hardness. The most rapid increase of the maximum induction and the most rapid decrease of the coercive force and the mechanical hardness are limited to the temperature regions of 200° to 300° C.

Beyond the maximum value of B_m there is a gradual decrease in the value of the induction as the steel passes through the troostitic and sorbitic states until the specimen is in the annealed condition. The annealed (pearlitic) condition is indicated by rapidly decreasing values of the residual induction, and constant values of the coercive force and mechanical hardness. Beyond the annealing temperature the only changes occurring are an increasing coarseness of the structure. Such coarseness is indicated by a continued decreasing value of the residual induction. The maximum value of the residual induction corresponds quite closely to the transition point between troostite and sorbite.

The high initial values of both the maximum and residual inductions after oil quenching indicate that most of the cementite has already been precipitated from the solid solution and that the structure is mostly sorbitic in nature. Such a structure is also indicated by the low values of the coercive force and the mechanical hardness. The increasing value of the maximum induction indicates the slow change through sorbite to pearlite. Beyond a temperature of 750° C. the magnetic characteristics agree in numerical values and thus indicate the physical similarity of the water and oil-quenched specimens in the annealed state.

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[1] Tammann, *Zeitschrift, für Physchalische Chemic*, Vol. 65, p. 79 (1908).

Fig. 5 represents the results for a specimen containing low percentages of several alloying elements. Chemical analysis indicates the following composition:

Carbon	0.64	per cent
Manganese	0.51	"
Phosphorus	0.013	"
Sulfur	0.038	"
Silicon	0.21	"
Nickel	0.63	"
Chromium	0.58	"

The magnetic characteristics of this alloy steel when quenched in water are similar to those of the carbon steel with similar quenching. However there is very little difference between the magnetic properties of the alloy steel under the two conditions of quenching except at low drawing temperatures. This agreement of the properties clearly indicates the effect of the presence of the alloying elements on the retardation of the transformation through the critical range. In carbon steels low values of the maximum and the residual inductions, and high values of the coercive force indicate extreme mechanical hardness. It is also true of this alloy steel but in addition it presents the anomaly, first observed by Mathews[1], that while oil quenching produces a magnetically harder substance, mechanical tests indicate the opposite effect.

Many theories have been advanced to explain the hardening of steel, but none of them satisfactorily explain the phenomenon. Sauveur[2] clearly presents existing conditions when he says: "It would seem as if the methods used to date for the elucidation of the complex problem of hardening have yielded all they are capable of yielding and that further straining of these methods will only serve to confuse the issue, a point having been reached when this juggling, no matter how skillfully done, is causing weariness without advancing the solution of the problem. The conclusion seems warranted that new avenues

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[1] Mathews, *loc. cit.*

[2] Saeuveur. International Engineering Congress, San Francisco, 1915.

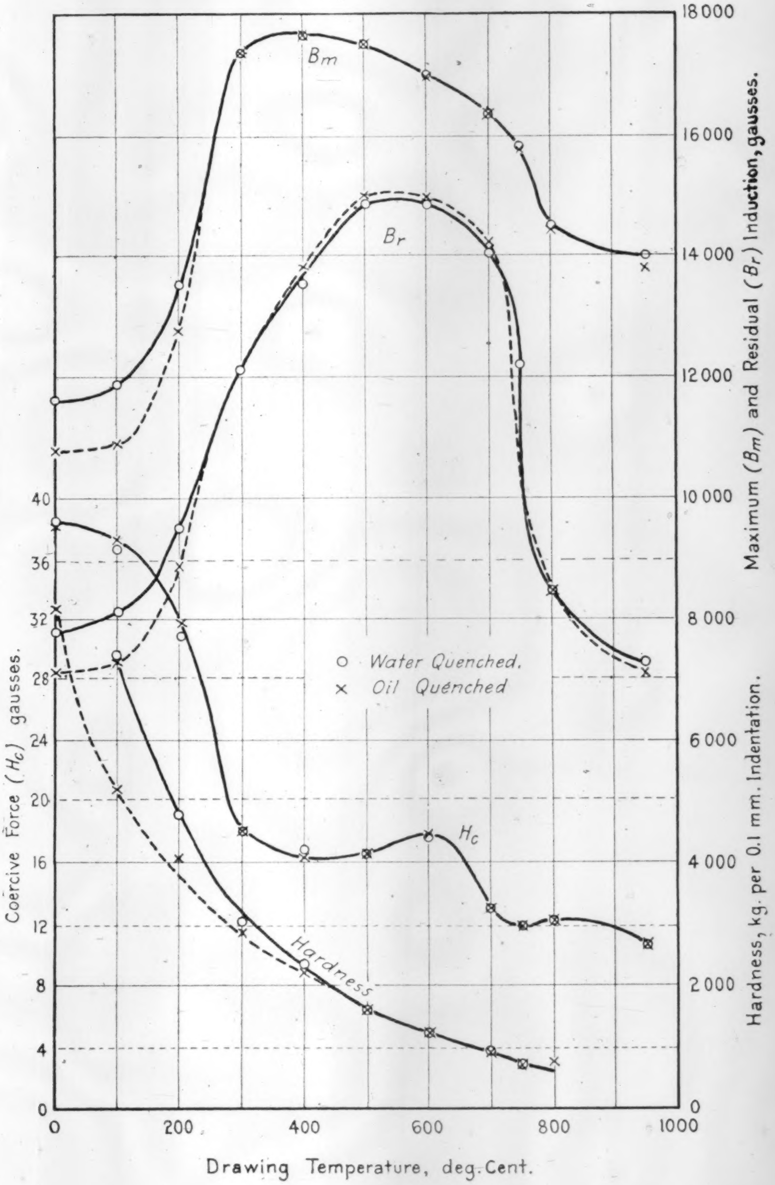

FIG. 5.—Effect of Heat Treatment on the Maximum Induction (B^m), Residual Induction (B_r), Coercive Force (H_c), and Mechanical Hardness of an Alloy Steel. Composition: C, 0.64; Mn, 0.51; P, 0.013; S, 0.038; Si, 0.21; Ni, 0.63; Cr, 0.58.

of approach must be found if we are ever to obtain a correct answer to this apparent enigma."

It is the opinion of the writer that magnetic analysis offers such a new avenue of approach toward the final solution of the many complex problems which confront the metallographer. For if the validity of Tammann's[1] law is accepted then the rapid increase of the normal induction and also the residual induction in the water-quenched carbon-steel specimen, within the temperature limits of 200 to 400° C., indicates that the cementite in such a specimen is in solid solution with the ferrite, and on being heated is precipitated from the solution. As these changes in the magnetic properties are accompanied by decreasing values of the mechanical hardness, within approximately the same temperature limits, the magnetic data indicate that the hardness (mechanical as well as magnetic) of martensite is due to the solid solution of the cementite and ferrite. Though such a method of investigation may not give the final answer to some of the complex problems of the metallographer, yet it will furnish additional evidence in favor of certain theories already existing.

PREDICTION OF THE MECHANICAL PROPERTIES.

Magnetic analysis has for its immediate and practical purpose the prediction of the mechanical properties of magnetic materials, such as carbon and alloy steels, based upon a knowledge of their magnetic properties. For its accomplishment a definite relationship between any given set of magnetic characteristics and certain mechanical properties is necessary. That such a definite relationship exists is no longer questioned. In an earlier paper of Burrows[2] he says: "Experimental evidence seems to point to the conclusion that there is one and only one set of mechanical characteristics corresponding to a given set of magnetic characteristics, and conversely there is one and only one set of magnetic characteristics corresponding to a given set of mechanical characteristics." However, the derivation of a direct numerical or analytical relationship seems to be an almost hopeless task.

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[1] Tammann, *loc. cit.*

[2] Burrows, *Bulletin*, U. S. Bureau of Standards, Vol. 13, No. 2, p. 173 (1916).

Before outlining what seems a more direct means of final attainment, it is perhaps advisable to mention some of the previous attempts at correlation and to discuss some of the difficulties encountered in such correlation.

Many experimenters have attempted to obtain a relationship between the normal induction curves of specimens of steel, subjected to various heat treatments, as indicative of their mechanical properties. Foremost among such investigators are Devries,[1] and Burrows and Fahy.[2] The results of their investigations clearly indicate that for a steel quenched from a suitable temperature the normal induction, for given values of the magnetizing force, has always (except for very low fields) much lower values than for the same specimen in an annealed state. If the quenched specimen is drawn to various temperatures, the respective curves of normal induction for these different drawing temperatures will always have values greater than for the specimen in the quenched condition. However, some of these curves will have lower induction values than the annealed while others will have higher values, the relationship depending on the drawing temperature. This relationship is particularly true for induction at high values of the magnetizing force. For intermediate values of the magnetizing force some of these normal induction curves intersect. An inspection of such a complete set of graphs shows a complex relationship which makes the problem of correlation a most difficult if not quite hopeless one when approached in this manner.

In view of this complexity and also from the very nature of the normal induction curve this method of attack does not give promise of satisfactory results. The writer believes that the maximum value of the induction (B_m) at moderately high values of the magnetizing force along with the corresponding hysteresis constants, the residual induction (B_r) and the coercive force (H_c) give much greater promise of yielding results of practical value in this field of research. Two methods of analysis will be discussed. In the first of these an attempt at correlation by direct comparison will be made, while in the second method "limiting values" of these quantities will be chosen as indicative of the mechanical properties of the material as a function of the mechanical and thermal treatment. The latter method of correlation, for want of a better term, will be called the "method of limiting values."

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[1] Devries, *Revue de Metallurgie*, Vol. 10, p. 141 (1913).

[2] Burrows and Fahy, *loc. cit.*

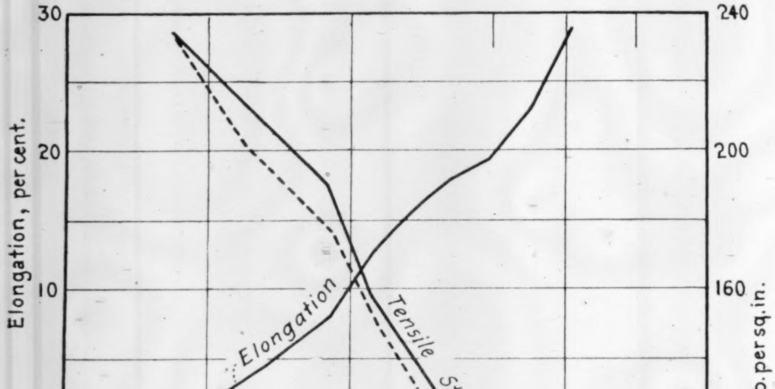

FIG. 6.—Effect of Heat Treatment on Tensile Strength, Elastic Limit, Reduction of Area, and Brinell Hardness of a Manganese Steel (Bullens).

In Fig. 6 the data[1] on the tensile strength, the elastic limit. and the elongation for a manganese steel commonly used in the manufacture of rifle barrels are plotted against the drawing temperature as the independent variable. The composition of this steel is 0.45 – 0.55 per cent carbon and about 1.25 per cent manganese. The values of the tensile strength and the elastic limit are somewhat higher than are generally found for steel of this particular composition, although for the immediate discussion the data serve just as useful a purpose.

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[1] Bullens, "Steel and its Heat Treatment," pp. 388–389.

The Brinell hardness data are for a 0.65-per-cent carbon, 1.32-per-cent manganese steel. This difference in the composition of the specimens from which the mechanical data are taken, however, does not in any way detract from the value of the discussion which follows.

In the curves of Fig. 7 the magnetic characteristics of a specimen of manganese steel of a similar type are plotted against the drawing temperature as the independent variable. It has the following composition:

Carbon	0.45 – 0.55	per cent
Manganese	1.10 – 1.35	"
Phosphorus	0 – 0.08	"
Sulfur	0 – 0.06	"
Silicon	0.20 – 0.23	"

The experimental procedure was generally as follows: The specimen was quenched from a suitable temperature and the three magnetic quantities (B_m, B_r and H_c) were determined at a maximum magnetizing force of 150 gausses. It was then subjected to repeated heat treatments and finally annealed at a suitable annealing temperature. Between these successive heat treatments the magnetic quantities were determined.

None of these quantities bears a simple relationship to the heat treatment. The general form of these curves is quite complex, but that of the coercive force is the least so.

Correlation by Direct Comparison.—Of the magnetic quantities and the mechanical constants, the only ones that give any promise of direct correlation are the coercive force and the Brinell hardness. Burrows and Fahy[1] have already indicated the existence of such a general relationship between these quantities and based on this relationship have made a practical

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[1] Burrows and Fahy, *loc. cit.*

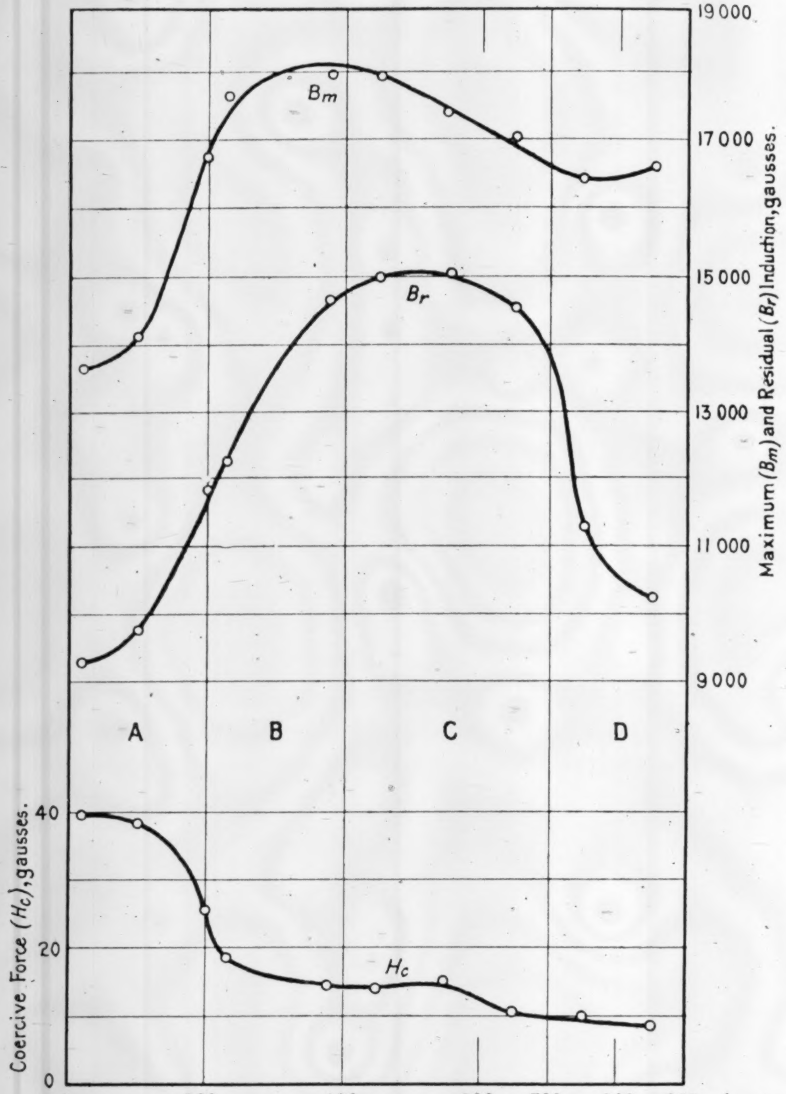

FIG. 7.—Effect of Heat Treatment on Maximum Induction (B_m), Residual Induction (B_r), and Coercive Force (H_c) of a Manganese Steel.

application of magnetic tests for the prediction of the mechanical hardness of small tools such as drills and knife blades. For convenience of comparison these graphs are reproduced in Fig. 8. It is quite apparent that no direct, or at least no simple relationship can be obtained between even these two properties, although the coercive force is undoubtedly a suitable criterion for the estimation of the Brinell hardness. High values of the coercive force undoubtedly indicate a corresponding value of the Brinell hardness, while low values indicate lower but varying degrees of hardness. It is also quite evident that this magnetic quantity, alone, is not sufficient to precisely define any definite value of the hardness, but only indicates the degree of hardness within a definite region.

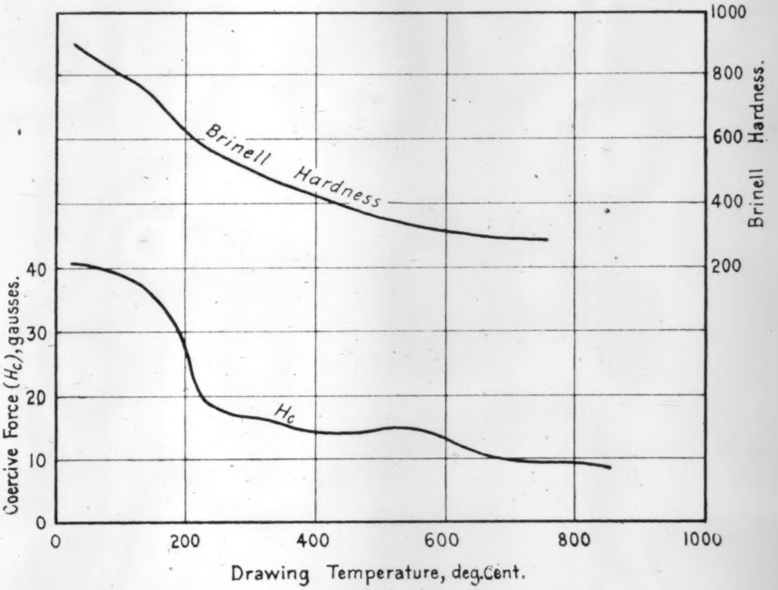

FIG. 8.—Effect of Heat Treatment on the Brinell Hardness and Coercive Force of a Manganese Steel.

Method of "Limiting Values."—For the purpose of this discussion the coordinate sheet of Fig. 7 is divided into four regions designated by the letters *A*, *B*, *C* and *D*. The boundary values for these regions are chosen so as to indicate most clearly the respective distinguishing features of these regions. They correspond approximately with the temperature limits for hardened, tempered, toughened, and annealed conditions of carbon steels after quenching and subsequent drawing.

The method of "limiting values" consists essentially in choosing from among the three magnetic quantities, determined at a definite and moderately high value of the magnetizing force (150 to 200 gausses), two of the quantities which will definitely correlate it with its mechanical properties. One of these magnetic quantities will definitely limit the properties of the specimen tested to one of the four above mentioned regions, while the second one, if suitably chosen, will definitely locate it within the region. Having thus precisely located the position with regard to the drawing temperature the correlation with its physical properties is comparatively easy. It is of course assumed that the results for the mechanical tests for various heat treatments have been experimentally determined and plotted in a similar manner.

In region A the coercive force has its maximum value and the residual and normal inductions their minimum. The first has a decreasing value and the latter increasing values. This high value of the coercive force definitely limits the mechanical properties to group A while this characteristic along with either B_m or B_r defines it uniquely in regard to its physical properties.

Since the coercive force is almost constant in value throughout regions B and C it is not a suitable criterion for correlation. However, the maximum induction along with the residual induction definitely determines the physical properties. In region D suitable values of the residual induction and either the coercive force or the normal induction, respectively, may be used. Thus not only can any one region be definitely differentiated from all of the others, but by making use of two suitably chosen magnetic quantities, their numerical values uniquely define the mechanical properties.

The above discussion can readily be illustrated by presenting numerical examples. A value of the coercive force of 34 gausses definitely locates the region and with a residual induction of 10,800 indicates that the hardness is approximately 500 Brinell units. For a maximum induction of 17,500 and a residual of 15,000, we have the corresponding approximate values of the mechanical properties: Brinell hardness, 340; tensile strength, 124,000 lb. per sq. in.; and elongation, 18 per cent.

In the most general application the mechanical properties resulting from various treatments must be determined by the usual mechanical tests, while on specimens of similar composition and treatment the magnetic properties are also determined. The fundamental data for the complete correlation between these properties are then available, so that in other specimens whose mechanical properties are not known, these properties may be definitely predicted by magnetic tests.

In many cases it is only necessary to determine whether a finished product has received the proper treatment (either mechanical or thermal, or both) in order to meet practical service conditions. After having determined the magnetic characteristics of a series of samples of the product they may be subjected to actual performance tests. On the basis of the data of such tests, suitable limiting values of the previously determined magnetic characteristics may be chosen so as to define the physical properties necessary to meet satisfactorily the specified performance conditions.

In many practical applications it may not be advantageous or even possible to use constant values of the magnetizing force in the determination of the magnetic characteristics. This may be due to the fact that the shape of the specimen requires a design of apparatus by which the values of the magnetizing force may not be readily determinable. In such cases the magnetic tests may be made at a constant value of the maximum induction. The criteria for correlation would then be the residual induction and the coercive force. The curve for the residual induction would be much less concave in appearance than for constant values of magnetizing force and the coercive force would have a much larger range of values. But here again definite limiting values of these quantities based on actual destructive or performance tests could be chosen so as to define the mechanical properties within prescribed limits.

The fundamental relations for correlation by the method of "limiting values" having been established, it becomes essentially a problem for the engineer to design such apparatus as to meet not only the demands of a rigid magnetic test but also the conditions of the testing room on a rapid commercial basis.

CONCLUSION.

In this paper definite methods of investigation in magnetic analysis have been outlined. These methods are based upon the following experimental facts:

1. That the magnetic properties of a steel are indicative of the transformations which it undergoes with heat treatment; and
2. That a definite relationship exists between the magnetic and mechanical properties of a steel product.

The first of these experimental facts furnishes suitable criteria from which the metallographic structure of such a material may be inferred. Such a method of investigation will, it is believed, assist the metallographer in the solution of some of the complex problems which now seem impossible of solution.

The second of these is fundamental to the necessary correlation between the magnetic and the mechanical properties of steel products in the prediction of the mechanical performance of such materials. By using "limiting values" of suitably chosen magnetic quantities the mechanical properties of such material may be uniquely defined.

A SYSTEMATIC INVESTIGATION OF THE CORRELATION OF THE MAGNETIC AND MECHANICAL PROPERTIES OF STEEL.

BY N. J. GEBERT.

Since the publication of Scientific Paper No. 272 of the U. S. Bureau of Standards, on "The Correlation of the Magnetic and Mechanical Properties of Steel," a great deal of interest has been aroused in the magnetic test method. Possibilities of the practical application of this method have been shown in the paper, "Some Applications of Magnetic Analysis to the Study of Steel Products," by C. W. Burrows, submitted at the 1917 meeting of this Society.[1] Both of these papers contain the statement that the evidence seems to point to the conclusion "that there is one, and only one, set of mechanical characteristics corresponding to a given set of magnetic characteristics and conversely there is one, and only one, set of magnetic characteristics corresponding to a given set of mechanical characteristics."

The writer has failed to find in the literature definite test results covering those points which would have an immediate and practical appeal to the metallurgist who is concerned in the many problems arising in the heat treatment of steel. The lack of such data has possibly arisen from the fact that those who have carried out the pioneer work in magnetic analysis have been forced to devote considerable time to the development of magnetic testing apparatus which would be free of complications, while retaining sufficient accuracy in measurement. The method of making magnetic measurements adopted by this Society several years ago as standard[2] requires the preparation of two specimens, as near alike as may be, to permit the accurate testing of one, which means a considerable handicap in the routine testing work of the practical metallurgical engineer.

However, the recent developments in permeameter design now permit the testing of single specimens without sacrificing accuracy and have greatly simplified magnetic testing both from the standpoint of ease and time involved.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II (1917).

[2] "Standard Tests for Magnetic Properties of Iron and Steel (Serial Designation: A 34–18)," 1918 Book of A.S.T.M. Standards, p. 268.

The permeameter used in this investigation was one of the Fahy Simplex type,[1] slightly modified by the author to accommodate specimens of 4½ in. in length. The accuracy of the magnetic test results to be obtained by this modified apparatus was determined by a check test carried out by the U. S. Bureau of Standards on a sample bar, which showed extremely close agreement between the results obtained by the standard method and the simplex method.

Since a satisfactory method of testing finished or partially finished steel parts, which does not destroy the material, would be of great value in the study or inspection of heat-treated products, an investigation in the magnetic analysis of several representative steels under various stages of treatment was undertaken. The steels which were examined are as follows:

Nickel steel (0.38 per cent carbon, 3.50 per cent nickel);
Chrome-nickel steel (0.36 per cent carbon, 3.50 per cent nickel, 1.50 per cent chromium);
Straight carbon tool steel (1.00 to 1.15 per cent carbon);
Swedish chrome file steel (1.19 per cent carbon, 0.39 per cent chromium).

The magnetic tests were conducted on the finished standard tension specimens held in detachable threaded bushings to insure proper contact with the pole faces. They were encircled by a coil 2 in. long and ¾ in. inside diameter, thus covering the 0.505-in. section throughout its length. Both tension and Brinell tests were made in accordance with the standard practice.

The magnetic data obtained, which are given in Tables I and II, include the maximum induction (B_m) under a magnetizing force of 150 units; the residual induction (B_r), or that induction which persists in the specimen when the magnetizing force is reduced to zero; and the coercive force (H_c) or that *reversed* magnetizing force which is necessary to reduce the residual induction to zero. The product $B_m \times H_c$ is proportional to the hysteresis area and represents the energy absorbed by the material when it is successively magnetized and demagnetized. The above magnetic quantities are those more commonly employed in magnetic analysis.

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[1] *Chemical and Metallurgical Engineering*, Vol. XIX, Sept. 1 and 15, 1918.

All material was annealed prior to heat treatment. The specimens in each group were quenched in one heat, after being brought up slowly to temperature and held there 10 to 15 minutes. In drawing, the specimens were brought to heat slowly, held there 30 minutes and cooled in air. The furnace employed was of the wound electrical resistance type.

TABLE I.—NICKEL STEEL.

SPECIMENS WERE QUENCHED IN OIL FROM 1500° F. AND DRAWN AS STATED.

No.	Draw, deg. Fahr.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Brinell Hardness.	Maximum Induction, B_m.	Residual Induction, B_r.	Coercive Force, H_c.
1....	Anneal	89 000	27.0	54.9	179	19 470	10 940	6.1
2....	0	273 500	10.5	34.1	512	17 400	10 190	22.5
3....	212	271 200	11.0	38.0	512	17 000	10 030	23.0
4....	380	260 000	11.7	43.0	480	17 500	10 640	23.3
5....	450	230 000	13.0	50.0	460	19 900	12 100	13.0
6....	600	201 000	14.0	56.8	418	20 050	12 140	12.0
7....	700	180 300	14.4	58.0	375	20 050	12 160	11.5
8....	800	160 500	15.0	60.0	321	20 050	15 600	11.0
9....	900	145 500	17.5	60.8	302	20 080	15 470	10.4
10....	1000	132 300	20.0	61.5	269	19 600	15 300	10.3
11....	1200	107 500	24.0	66.5	225.	19 500	15 060	9.6
12....	1400	98 000	24.5	57.3	202	19 450	10 800	9.2

TABLE II.—CHROME-NICKEL STEEL.

SPECIMENS WERE QUENCHED IN OIL FROM 1500° F. AND DRAWN AS STATED.

No.	Draw, deg Fahr.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Brinell Hardness.	Maximum Induction, B_m.	Residual Induction, B_r.	Coercive Force, H_c.
1....	Anneal	96 000	22.0	41.8	180	18 760	11 470	6.4
2....	0	....	....	....	....	16 440	10 280	25.3
3....	212	....	....	....	....	16 300	10 010	25.5
4....	380	265 000	10.8	38.0	444	16 500	10 400	25.1
5....	450	250 000	10.8	41.0	410	19 540	12 180	14.8
6....	600	222 000	11.0	43.6	364	19 690	12 650	13.5
7....	700	212 000	12.0	45.0	351	19 600	12 900	13.3
8....	800	193 500	13.2	46.0	332	19 650	15 500	12.7
9....	850	178 000	15.5	47.5	311	19 640	15 480	12.3
10....	1200	126 000	22.5	59.0	228	19 270	15 230	11.0
11....	1300	118 000	23.5	55.4	217	18 840	13 100	10.5
12....	1400	111 500	23.5	50.9	207	18 040	11 140	10.0

The specimens drawn at 0 and 212° F. broke in the threads and tests were discarded.

The curves shown in Figs. 1 to 4 inclusive were plotted from the above data. Figs. 1 and 3 show the relation of the Brinell hardness to the hysteresis area ($B_m \times H_c$) of the two steels investigated, while Figs. 2 and 4 illustrate the relation of tensile strength to the hysteresis area.

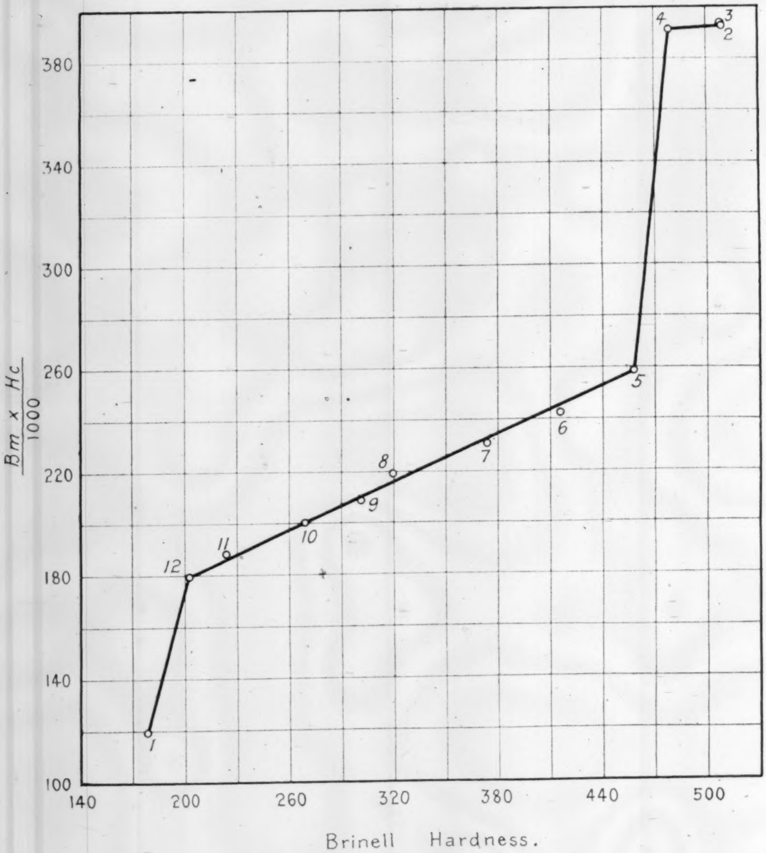

FIG. 1.—Nickel Steel. Relation of Brinell Hardness and Hysteresis Area.

Considering the fact that the magnetic data, so closely allied to the strength as expressed in tensile and Brinell hardness units, have been obtained by measurement of reaction to forces which leave the material entirely unchanged, the value of this method both for routine and research work is quite apparent. Referring to the values shown in Tables I and II, it will be seen that between the drawing temperatures of 380° and 450° F.

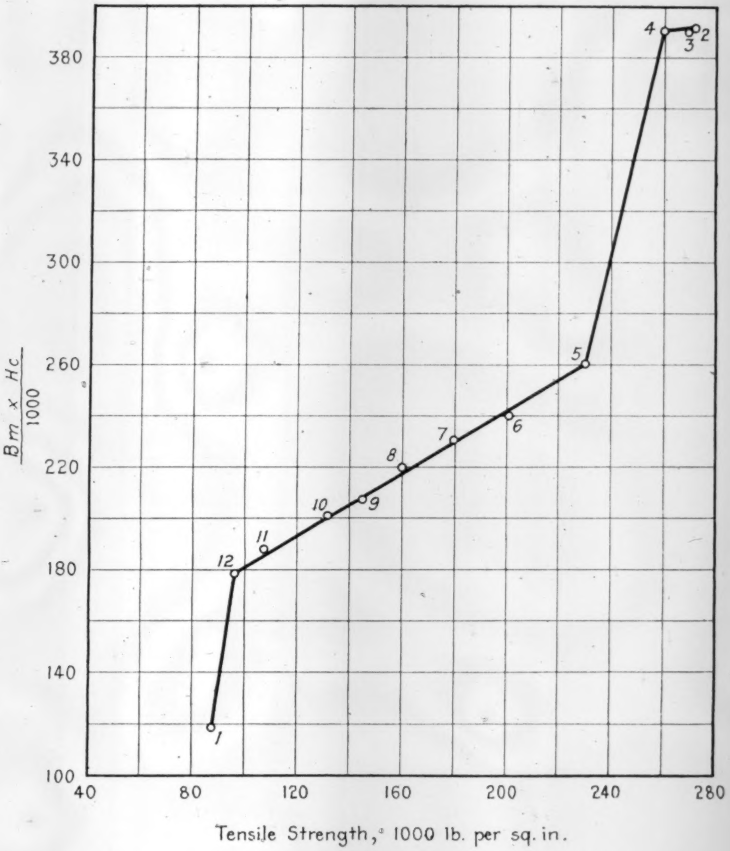

FIG. 2.—Nickel Steel. Relation of Tensile Strength and Hysteresis Area.

there is a considerable increase in the induction and residual induction and a corresponding decrease in the coercive force. It has been fully established that the cementite (Fe_3C) in a quenched steel largely exists in a state of solid solution. The point at which this cementite comes out of solid solution, the Ac_0 point, has been determined microscopically by many metallurgists and was magnetometrically measured by K. Honda.[1]

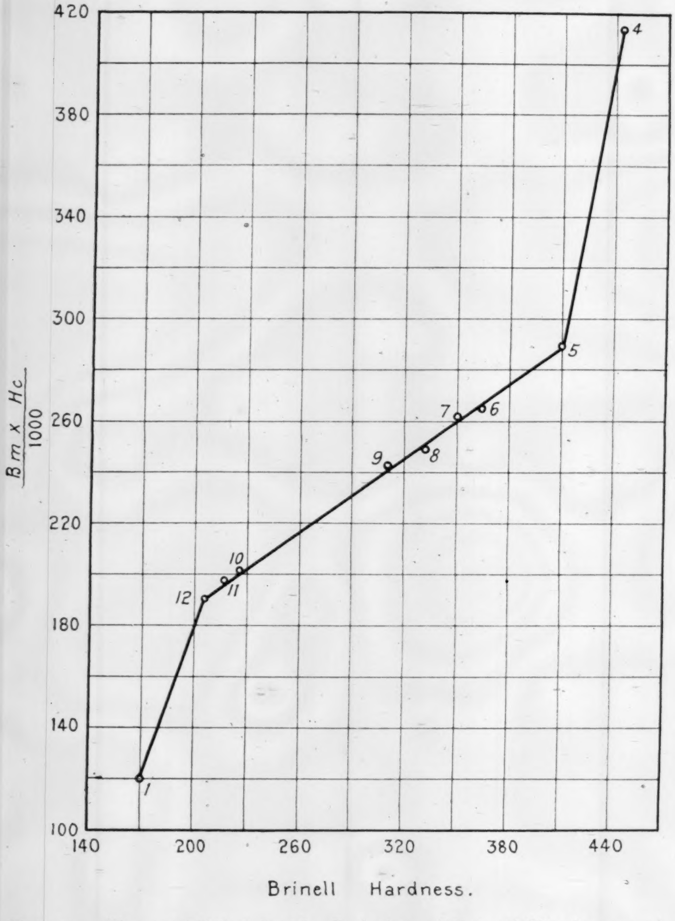

FIG. 3.—Chrome-Nickel Steel. Relation of Brinell Hardness and Hysteresis Area.

The curve shown in Fig. 5 is taken from this paper by Honda which shows the transformation point to be 215° C. (419° F.).

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[1] "Magnetic Investigation of the States of Cementite in Annealed and Quenched Steels," Science Reports of the Tohoku University, Vol. VI, No. 3.

On examining Tables I and II, we see that the intensity of magnetization of the quenched steels is very low. This is due to the fact that cementite is less magnetizable than ferrite, and when dissolved in ferrite the intensity of magnetization is decreased according to Tammann's Law.[1] On heating a piece

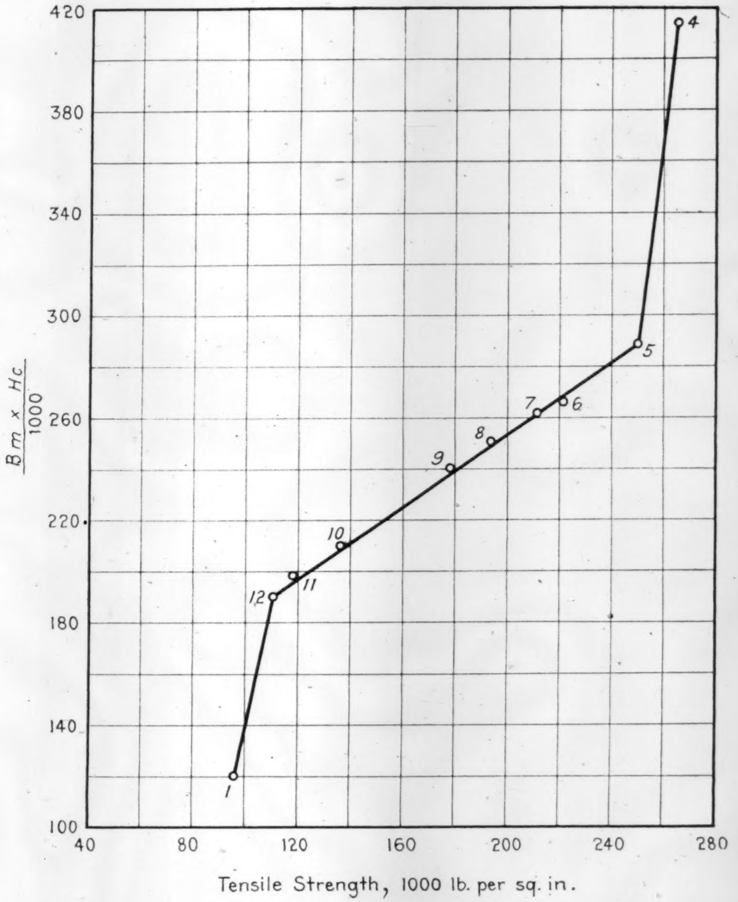

FIG. 4.—Chrome-Nickel Steel. Relation of Tensile Strength and Hysteresis Area.

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[1] *Zeitschrift für phys. Chem.*, Vol. 65, p. 79 (1908).

of steel in which the cementite is held in solid solution above the Ac_0, point, the cementite comes out of solid solution and the intensity of magnetization is increased to a great extent as shown in the specimen drawn at 450° F. The tensile strength and Brinell hardness show little change in this range, while the magnetic properties show a considerable increase in magnetization and a corresponding decrease in coercive force.

In this region the magnetic values will afford a better indication of the magnitude of the structural changes than either tensile or Brinell tests. By thus giving us such valuable information without injuring the specimen, magnetic analysis will permit tests which will enable us to clear up many difficulties in hardening practice.

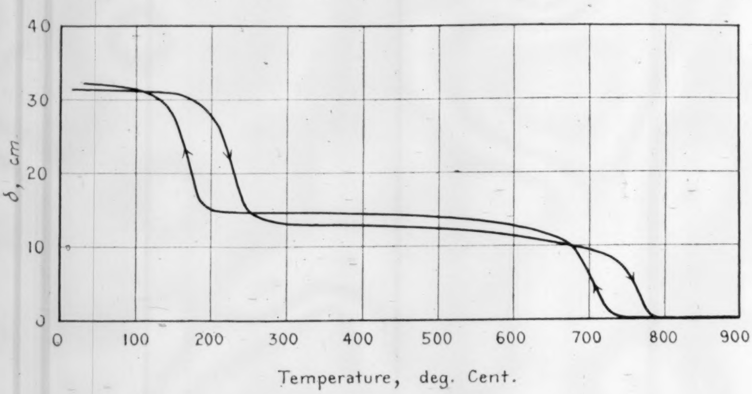

FIG. 5.—Transformation Curve (Honda).

The writer quite frequently met the following problem in the heat-treating of taper parts for roller bearings. Such taper parts, after quenching, are usually drawn at 375° F., or in many cases given a quick draw at 400° F. This quick draw consists of bringing the material up to heat slowly (in about one-half hour) and immediately removing from the bath upon reaching 400° F. In using this latter method, it frequently occurs that one batch passes the customary file test while the next lot is "dead soft" to the file and is rejected. The only method used at present for separating the soft from the hard is by the "feel" of the file. Magnetic testing offers convenient and rapid means for separating such unsatisfactory products from those successfully treated and would eliminate what is now to a considerable extent guesswork.

The increase in residual induction between the drawing temperatures of 700 and 800° F. can be explained through the transformation of the double carbide of iron taking place at about 750° F., as has been shown in the magnetic investigation by T. Ishiwara.[1] Ishiwara measured the magnetization of the steel while heating and cooling and obtained a variation in the magnetization just below and above this transition point.

While the tensile strength and Brinell hardness are in relation to the hysteresis area of a given steel, the residual induction shows in a very marked manner the structural changes which take place during heat treatment. For instance, in heating slightly above this transition point (750° F.), the tensile strength does not show any marked drop while the residual induction considerably changes (increases), indicating that the structure of the material has undergone transformations. Plotting the residual induction against drawing temperatures on both the nickel and chrome-nickel steels, the curves in Figs. 6 and 7 are obtained.

Magnetic data were also obtained of straight carbon tool steel and Swedish file steel when the materials were quenched in water from various temperatures and not subjected to a drawing temperature. Both these grades of steel are used extensively in practice, and since their great hardness does not permit of satisfactory Brinell hardness testing, it was very important to determine whether the magnetic characteristics afford a suitable index as to whether or not a proper quenching temperature was used. The values for induction and residual induction shown in Tables III and IV vary directly with the quenching temperatures and enable us to determine from what temperature the steel has been quenched. The variations of magnetic values are of such magnitude as to permit the detection of the slightest differences in quenching temperatures.

In order to ascertain whether a previous incorrect treatment could be covered up by a high quench or an anneal, the following tests were made. Material of the same chemical analysis as that represented in Table IV was investigated. The analysis of this Swedish file steel closely approximates that of steels used, for example, in balls and races. In the manufacture of these steels it is very important that the material shall not cool slowly from above the Ac_m point (about 1650° F.), as this brings about the rejection of the cementite to the grain boundaries. This frequently occurs in bars cooling from the forging or rolling opera-

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[1] "On the Magnetic Analysis of Carbides Found in Different Kinds of Steel," *Scientific Reports*, Tohoku Imperial University, Vol. VI, No. 5.

TABLE III.—STRAIGHT CARBON TOOL STEEL.

SIZE OF SECTION: ½ IN. SQUARE.

Treatment: Quenched in Water from Temperatures Indicated, deg. Fahr.	Maximum Induction, B_m.	Residual Induction, B_r.	Coercive Force, H_c.
1340	15 400	9 360	18.8
1360	13 980	8 860	32.0
1380	13 370	8 470	37.5
1400	12 450	7 980	45.0
1420	12 050	7 720	46.0
1440	11 640	7 600	47.8
1460	11 440	7 400	49.0
1480	11 040	6 720	50.0
1500	10 340	5 980	50.0
1520	9 940	5 740	50.0
1540	9 640	5 560	49.8
1560	9 340	5 320	49.2
1580	8 860	4 800	48.0
1600	8 190	4 330	45.3
1630	Cracked badly		

TABLE IV.—SWEDISH FILE STEEL.

SIZE OF SECTION: ½ IN. SQUARE.

Treatment: Quenched in Water from Temperatures Indicated, deg. Fahr.	Maximum Induction, B_m.	Residual Induction, B_r.	Coercive Force, H_c.
1350	15 190	9 940	14.0
1400	12 890	8 880	47.5
1430	12 620	8 430	47.8
1450	12 240	8 230	48.7
1480	11 910	7 760	50.4
1500	11 390	7 440	50.4
1530	11 240	7 150	50.0
1550	11 070	6 980	48.4
1600	9 690	5 540	44.3
1630	Cracked badly		

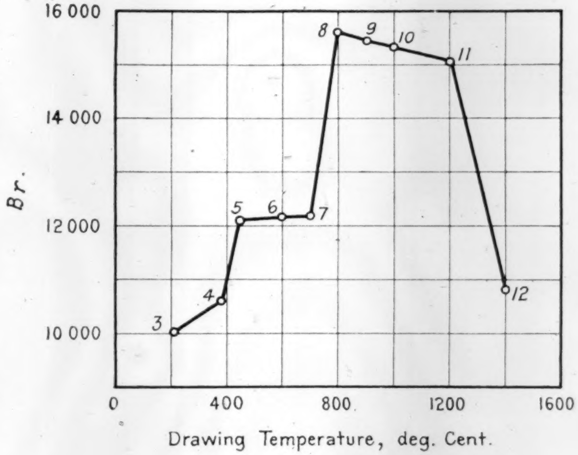

FIG. 6.—Nickel Steel. Relation of Drawing Temperature to Residual Induction.

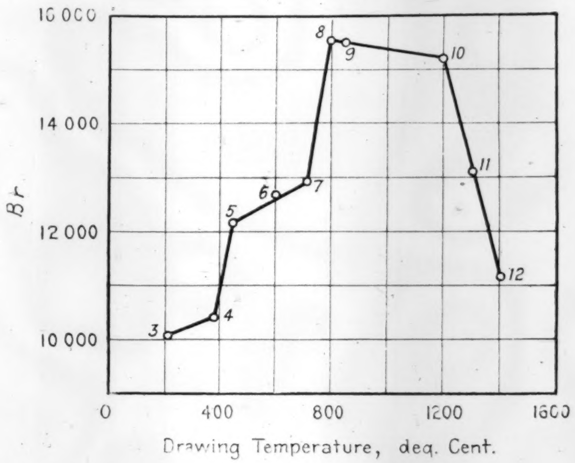

FIG. 7.—Chrome-Nickel Steel. Relation of Drawing Temperature to Residual Induction.

tions, possibly lying on hot ashes or dirt, or being rolled or forged at an extremely high temperature. Material in this condition, upon subsequent hardening, would be extremely brittle and unfit for many uses.

In Table V, the magnetic characteristics of this material in the conditions as received, and when cooled in air and cooled in the furnace respectively from a high temperature, then annealed and hardened, are shown. It will be seen that neither an anneal at 1380° F. nor a quench in water from 1450° F. could cover up magnetically the previous incorrect cooling. The magnetic values still show the material to be structurally different, especially as regards residual induction.

The data here presented form a report of an initial investigation which shows very promising results and certainly warrants considerable additional work along these lines. In magnetic analysis we have a method of test which is unique in that it is capable of giving results of value under procedure which has no permanent influence on the material examined. No other known successful testing method possesses this important advantage. Magnetic analysis enables us to draw distinctions between steels where the present methods of test fail to make sufficient differentiation. The possibilities of magnetic analysis in the examination, study, and duplication of steel products which have given exceptional performance in actual service are apparent.

TABLE V.—SWEDISH FILE STEEL.

Treatment.	Maximum Induction, B_m.	Residual Induction, B_r.	Coercive Force, H_c.
eceived	15 540	11 530	13.3
1650° F., cooled in the air, annealed at 1380° F	15 350	10 440	15.5
1650° F., cooled in furnace, annealed at 1380° F	15 110	9 720	14.0
650° F., cooled in air, quenched 1450° F. in water	11 770	8 880	52.
F., cooled in furnace, quenched 1450° F. in water	11 670	7 760	51.3

Magnetic analysis of iron and steel should be of the same value to the metallurgist as chemical analysis is to the chemist. Microscopic investigation of steel gives results which are qualitative, rarely quantitative. The preparation of micro-sections often releases stresses in the metal to be studied, and, in general, tests of this kind require a great deal of individual judgment and experience. The magnetic tests are expressed in definite figures, permitting quantitative measurements, and the interpretation of test data leaves no room for conjecture.

THE MAGNETIC-MECHANICAL ANALYSIS OF CAST IRON.

BY S. R. WILLIAMS.

In a recent paper by Rood[1] on the relation between tension and magnetic permeability, he comes to the remarkable conclusion that cast iron does not have its permeability affected by tension. So far as the present author knows the specimens of cast iron which Rood studied are the only samples on record in which tension does not affect the magnetic permeability of ferromagnetic substances.

The presence of the Villari effect[2] in all ferro-magnetic substances seems to fit into our present theories of magnetization, and any exception to the general rule is always of immense interest. It seemed, therefore, quite worth while to make another study of the behavior of cast iron magnetically while it was being subjected to tension. In this connection it gives me pleasure to speak of the courtesy shown by the Interstate Foundry Co. of Cleveland, Ohio, who not only furnished various samples of cast iron but also supplied the accompanying chemical analysis of the same.

This paper gives results on two entirely different specimens of cast iron, measurements being carried out also for two samples of the same constitution. Three rods were thus measured and are numbered 11, 12 and 21 respectively. All of the rods had the same length, 42 cm.; Nos. 11 and 12 were 0.58 cm. in diameter and are known to the trade as gray cast iron.

CHEMICAL ANALYSIS, NOS. 11 AND 12.

Silicon	3.100	per cent
Sulfur	0.095	"
Phosphorus	0.763	"
Manganese	0.350	"
Total Carbon	3.200	"

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[1] Rood, *Electrical World*, Jan. 13, 1917, Vol. 69, p. 94.

[2] Villari, *Poggendorf's Annalen*, Vol. 126, p. 87, 1865; Ewing, "Magnetic Induction in Iron," etc., pp. 196, 224, 236, 3d. Ed. 1900.

No. 21 was 0.64 cm. in diameter. It is known on the market as semi-steel cast iron and carries about 12 per cent of steel.

CHEMICAL ANALYSIS, NO. 21.

Silicon	2.100 per cent
Sulfur	0.085 "
Phosphorus	0.250 "
Manganese	0.600 "
Total Carbon	3.050 "

In his book, "Applications of Mathematics to Physics and Chemistry" (p 47 et seq.), Sir J. J. Thomson has discussed the reciprocal relations which exist between magnetism and stress. He has pointed out that "it is possible from theoretical considerations to predict the general character of the effects of stress from a knowledge of the changes of dimension caused by magnetization." This has been experimentally confirmed by scores of workers[1] since then. A principle[2] which seems to be pretty well established in magnetic observations is that "there is one, and only one, set of mechanical characteristics corresponding to a given set of magnetic characteristics, and conversely there is one, and only one, set of magnetic characteristics corresponding to a given set of mechanical characteristics." This all means to say that if a rod of cast iron shows no change in permeability due to tension, then it should show no change in length due to a magnetic field. An important confirmation of the fact that cast iron does not change its magnetic permeability when stretched would be an investigation of its length when subjected to a magnetic field. Both tests were applied to the rods studied in this paper and both indicate that a change in magnetic permeability should occur due to tension. The change is small, but that is what we should expect from the electron theory of magnetization. It was so small that the ordinary magnetometer method for showing variation in intensity of magnetization did not show a variation due to change in tension. The ballistic induction method proved better because larger tension could more easily be applied.

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[1] Bidwell, *Philosophical Transactions*, 1888, A, p. 205; Chree, *Philosophical Transactions*, 1890, A, p. 329.

[2] Günhut and Wahn, *Zeitschrift Electrochemie*, Vol. 15, p. 894, 1909; Burrows, *Scientific Paper No. 272*, U. S. Bureau of Standards, March, 1916; Williams, *Journal*, Cleveland Engineering Soc., Jan. 1917, p. 183.

Among the various forms of iron, one would expect in cast iron the least change in magnetic permeability due to tension, also the least change in length due to a magnetic field. This would seem to be closely associated with some work by Barus and Strouhal,[1] who found that among various forms of iron, cast iron had the lowest specific resistance.

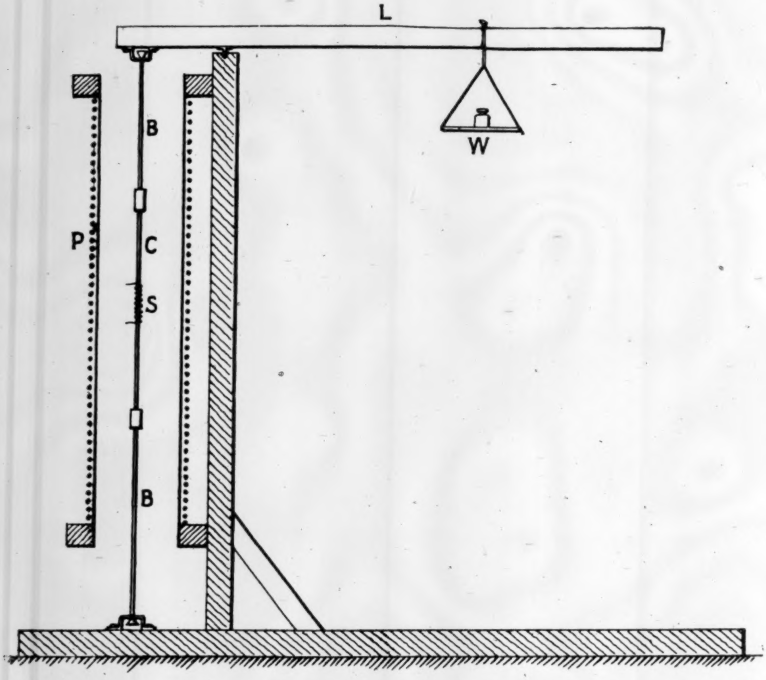

FIG. 1.—Apparatus to Determine Change in Magnetic Induction Due to Tension.

CHANGE IN MAGNETIC INDUCTION DUE TO TENSION.

Inasmuch as every piece of cast iron, in fact any specimen of ferromagnetic substance, has its own peculiar *B-H* curve, it did not seem important enough to determine the absolute value of *B* in the specimens studied, so the values of the deflections of the galvanometer by the ballistic reversal method were used to show variation of induction with varying tension. The important point was the determination of the presence or absence of the Villari effect. The rods were mounted inside of the solenoid *P*, Fig. 1, whose length was about double that of the rods *C*, and whose constant was 28.08 gausses per ampere. A lever device *L*, with sliding weight *W*, was employed for varying the tension. *B*, *B* are the brass extensions of the rod *C*. For the secondary coil *S*, 160 turns of No. 27 insulated wire were wound directly on the rod *C*, so as to form a single layer 8 cm. long. This secondary coil was connected in series with a ballistic galvanometer and proper resistance. The field was carried up step by step with the reversal process, demagnetization occurring before each series of readings by a decreasing A. C. field. Each reading in Table I is the average of six observations. The results are the percentage increases in induction on adding different loads at various field strengths.

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[1] Barus and Strouhal, *Bulletin No. 14*, U. S. Geological Survey.

TABLE I.—PERCENTAGE INCREASE IN INDUCTION FOR VARIOUS TENSILE LOADS.

ALL VALUES IN PER CENT.

Load, kg.	Field, gausses				
	28	56	84	112	140
ROD NO. 11.					
0	0	0	0	0	0
50	1.5	0.4	0.6	0.3	0.2
100	2 4	0.7	0.8	0.5	0.4
150	4.5	1.4	1.5	0.8	0.4
ROD NO. 12.					
0	0	0	0	0	0
50	1.6	0.6	0.5	0.5	0.7
100	1.8	1.0	0.4	0.8	0.3
150	2.6	1.5	0.5	0.8	0.4
ROD NO. 21.					
0	0	0	0	0	0
50	.6	0.9	0.3	0.2	0.4
75	1.9	0.8	0.5	0.2	0.5
100	2.7	1.3	1.0	0.5	0.5

The values for the loads are given as though the loads hung directly on the rods. So far as the readings were carried the induction was increased by loading. There appears to be no

Villari reversal point. This will be brought out more clearly in the data on reciprocal relations.

CHANGE IN LENGTH DUE TO MAGNETIZATION.

The rods were next transferred to another vertical solenoid whose constant was 140.85 gausses per ampere. The optical device for measuring the change in length has been described in a former paper.[1] In Fig. 2 are plotted the curves showing the different values of magnetic change in length with varying magnetic field. All of the curves become asymptotic to the field axis, indicating that there is no Villari reversal point, and thus corroborate the results found in the reciprocal effect given above. Each point on the curves gives the average of four readings and shows the total elongation of the rods for the different field strengths.

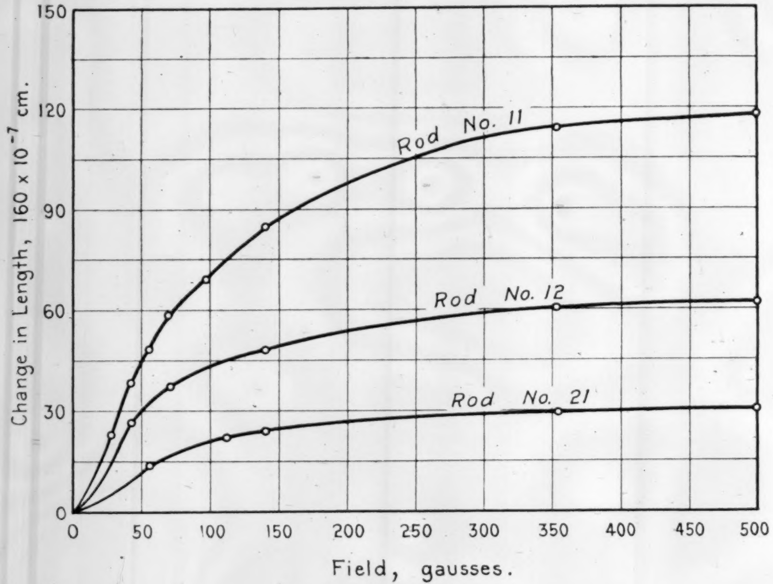

FIG. 2.—Showing Relation Between Change in Length of Cast-Iron Rods with Variations in Magnetic Field.

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[1] *Physical Review*, Vol. 34, April, 1912, p. 258.

Rods Nos. 11 and 12 have the same chemical constitution and yet their magnetic changes in length and induction curves show a wide variation. In the opinion of the writer there are two ways in which this might have come about; first, there is the possibility that in the casting process, as the rods cooled, the elementary magnets were caught in different modes of orientation; or, secondly, the final heat treatment must necessarily be different. This point of view also accounts for the fact that the induction curve for every ferromagnetic specimen is a curve peculiar to that particular specimen. Two rods cut from the same original specimen will never show quite the same induction curve. If the rods are rolled or drawn the original orientation of the elementary magnets is different in one specimen from that in another, and so a different induction curve is obtained. The writer is working up some experiments on rods built up electrolytically in a magnetic field. There should be a number of rods built up in this way, but with the magnetic field oriented differently with respect to the axis of the rod. Such an experiment ought to throw some light on this particular point.

SUMMARY.

By a direct and an indirect approach it has been shown that cast-iron rods, whose chemical compositions are given, have their permeabilities changed by tension. So important are the results of Rood that it would seem highly desirable that his cast-iron rods be tested by the method of change in length due to a magnetic field. Not infrequently the exception to the rule becomes the most important factor in developing a theory, and it would seem that the cast-iron rods studied by Rood are exceptions.

The author is indebted to Mr. R. B. Siddall, an advanced student in the Department of Physics, Oberlin College, for assistance in making the measurements herewith given.

DISCUSSION.

Mr. Devries. MR. R. P. DEVRIES (*presented in written form*).—There is a certain advantage in testing tools by the magnetic method, an advantage so obvious that it need hardly be mentioned. The great cost of modern high speed steel tools, taken in conjunction with the difficulty of testing a finished tool by any method now known, would make the magnetic test seem ideal for this purpose.

Accordingly, some years ago I started testing tools by the magnetic method, starting with the simpler problem such as testing out circular saws. The problem in this particular case was that saws made from material which had been accepted by the laboratory as being both chemically and physically correct would sometimes come out from the hardening heat so soft that they could be filed without any difficulty. In different lots of saws there would very often be a certain percentage that came out file-hard and apparently of good microstructure, while others would be soft to the file and apparently of the same microstructure.

Although it is a well-known fact—not always borne in mind, however—that the quality of the high speed tool is not entirely dependent upon its extreme file hardness, there is a decided bias in favor of the extremely file-hard high speed tool in the minds of most makers and users. The magnetic test showed that there was practically no difference in the residual magnetism and coercive force between saws which were file-hard and file-soft. Furnace temperatures were checked up on the different lots of saws and it was found that the saws which came out file-soft were oftentimes heat-treated in exactly the same way so far as temperature and duration of time in the furnace are concerned as the file-hard ones. The soft saws were therefore invariably tested magnetically, and from the experience thus gained with all classes of saws, upper and lower magnetic test limits were established. If a saw was file-soft and came within these upper and lower limits, it was passed without calling for rehardening.

Mr. Devries.

It may be mentioned here in passing that on rehardening such file-soft saws, the residual induction and the coercive force were never raised in value, and very seldom was the file hardness increased by any appreciable amount.

The conclusion was reached from these tests that any steel saw which showed the desired magnetic characteristics, had the proper quantity of carbon, chromium and tungsten in solid solution, and therefore could be safely passed. The trouble encountered in hardening high speed saws was, therefore, to a certain extent eliminated, since before this test was established it had been customary to harden and reharden the saws until they became file hard, a proceeding which even if it is prefaced by careful annealing is not at all desirable, since the men who are doing this work will finally bring the saw up to a very much higher heat in order to avoid rehardening a tool which their foreman has told them is unsatisfactory.

In giving this simple instance of the application of magnetic testing, I do not mean to imply that more complex tools than saws cannot successfully be tested magnetically. It has been found that tools varying in weight by many grams, when they are of the same shape and general design, may successfully be tested in this way by applying a certain weight or volume factor to the magnetic test. A great deal of work has been done on more complicated tools, using such a factor, but the applications at this time have not extended to acceptance or rejection of tools on that basis.

Mr. Unger.

MR. J. S. UNGER (*presented in written form*).—To have real commercial value, any form of testing material should have these requisites:

1. The result should show important properties of the material, to determine its fitness for service.
2. It should be quickly and cheaply executed.
3. It should not injure the material tested.

Almost every type of test requires a portion of the material for execution, and in this particular magnetic testing is advantageous.

Magnetic testing is one of the latest methods for testing steel products, but the several discussions presented do not show that where magnetic disturbances exist, the material is unfit for service. If we can determine where a rail has been gagged, where

Mr. Unger. a saw slot or bolt hole is located, where the rail rests on a tie; if we can determine whether the rail has been slowly or rapidly cooled, or whether it is piped, why not mark such locations on a new rail and then put it into service and observe if it will fail at the marked points. Until such has been done, it is unwise to draw conclusions as to the value of such tests.

It appears that a new rail is freer from magnetic disturbances than a used rail, which is to be expected, as rails are stressed in service leaving resulting strains. If such strains are dangerous, they may be detected and the rail removed. We must admit that a material such as a rail must show fatigue after the severe service a rail receives.

It is very difficult in this discussion to adhere strictly to magnetic testing, especially when transverse fissures and remedial measures are introduced. If gagging be the cause of transverse fissures and the gagged points can be located by magnetic testing, all rails should fail at such points, as all are gagged. This does not explain why some transverse fissures occur at the ends of rails which are not gagged. A simpler method to determine the gagged point would be to examine the broken scale on the side of the rail.

To show that magnetic disturbances are present without being able to show their close relation to the physical and mechanical properties of steel, is insufficient evidence to prove that magnetic testing has reached the point at which it will show that injurious or destructive influences are at work.

Mr. Burrows. MR. CHARLES W. BURROWS (*Closing discussion by letter*).—In closing this discussion it is desirable to emphasize two phases which apparently are not clear to those who have not been able to make a critical reading of the papers presented. In the first place, while most of the experimental work has been devoted to a groping after suitable detailed methods and in clearing away the underbrush of irrelevant matter, several important results have been reached which form a substantial foundation for future work. In substantiation of this statement let me mention the following twelve points which have been brought out in the papers just presented:

1. The principle that there is a very close relationship between the mechanical and magnetic characteristics of steel is established on a firm basis.

Mr. Burrows.

2. Laboratory tests show that the commercial application of magnetic analysis to shop routine practice is practicable.

3. For a given chemical analysis the quenching temperature of a steel can be determined with considerable precision by magnetic means.

4. For a given chemical analysis and quenching temperature the drawing temperature of a steel can be determined with considerable precision by magnetic means.

5. A magnetic examination of an object, such as a knife blade or a ball-bearing race, as it comes from the quenching bath, will tell whether or not it is cracked or has been so badly strained in quenching that cracks are liable to develop under further thermal or mechanical handling.

6. The tests on rails clearly show that structural irregularities result in magnetic disturbances. In one instance, that of the hard steel spots located in the rail head through magnetic means, we have a rail flaw sufficient to prohibit the use of the rail in mainline traffic.

7. Dudley has definitely located by magnetic means a number of interior transverse fissures.

8. The presence of soft spots and cracks in ball-bearing races has been detected by magnetic means.

9. By use of the "limiting values" of suitably chosen magnetic constants, the determination of the mechanical properties of steel is greatly simplified.

10. Gebert has shown that incorrect cooling of steel from the rolls may be determined even when subsequent thermal treatment intervenes.

11. Gebert shows that a linear relation exists between his magnetic characteristic and the Brinell hardness and tensile strength.

12. Magnetic analysis is employed in one plant in its routine shop testings.

The second point that needs clarifying is the present state of the art of magnetic analysis. While much has been accomplished and a firm foundation established, much remains to be done. The superstructure must be erected. We must determine what the various magnetic indications mean in terms of mechanical fitness. Magnetic and mechanical tests must be run conjointly.

Mr. Burrows. The man who denies the possibilities of magnetic analysis to-day because of its not being a finished instrument of investigation would have rejected the aid of microscopic analysis or chemical analysis or any of the other means of testing in the early stages of these arts, which have since proved of so great service to man.

However, the pages of history are filled with the stories of men of short vision who have attempted to block the wheels of progress. Even so great a man as Daniel Webster opposed with all the power of his masterful oratory an appropriation of $50,000 to establish mail communication with the Pacific Coast.

"What do we want of the vast worthless area," said Webster, "this region of savages and wild beasts, of deserts of shifting sands and whirlwinds of dust, cactus and prairie dogs? To what use could we ever hope to put these deserts, or these endless mountain ranges, impenetrable and covered to their bases with eternal snow? What can we ever hope to do with the western coast of three thousand miles, rockbound, cheerless and uninviting with not a harbor in it? What use have we for such a country? Mr. President, I will never vote one cent from the public treasury to place the Pacific Coast one inch nearer Boston than it is to-day."

MODERN HIGH SPEED STEEL.

By John A. Mathews.

SUMMARY.

In this paper the origin of Modern High Speed Steel is discussed. The change from the old type of air-hardening steels to the modern type of high speed steels is obviously associated with the announcement of the Taylor-White process. A comparison of analyses in 1901 and 1902 shows that in the latter year this change had already taken place in America, England and Germany. It will probably never be known who made the first low-carbon high-tungsten high speed steel.

The quality of "red hardness" first described by Taylor is discussed. Reference is made to investigations conducted upon the hardening and tempering qualities of high speed steels in the endeavor to discover a simpler index or guide to the quality of such steels without resorting to expensive and time-consuming cutting tests.

Tests by the writer on four typical steels are described, including electrical and magnetic tests as well as the determination of hardness. The importance of mineralogical hardness as distinguished from "red hardness" where the cutting conditions are not severe is emphasized.

The paper is concluded with brief reference to the introduction of various elements in high speed steel, notably, vanadium, cobalt and uranium. It is concluded that the term "Modern High Speed Steel" may be considered as referring to the product since the introduction of vanadium, as no generally accepted improvement has been made in high speed steel since that time.

MODERN HIGH SPEED STEEL.

By John A. Mathews.

After accepting the invitation of the Committee on Papers and Publications to present a paper on the announced subject, the writer began to wonder just what the Committee meant by "Modern" High Speed Steel. A product that is of less than twenty years' standing is certainly modern when compared with crucible tool steel which has been manufactured for about 170 years, and even the air-hardening steels which preceded high speed steel resulted from the investigations of R. F. Mushet about fifty years ago.

I have been deeply interested in everything pertaining to the history of the iron and steel business, but this latest product, high speed steel, seems to have sprung fairly fully developed from a variety of sources and at almost the same time, and I have been unable to show just when the change from the old type of air-hardening steels to the modern type of high speed steels took place. Obviously the change is associated with the announcement of the Taylor-White process; that is, the high heat treatment given these grades of steels as compared with the ordinary treatment of carbon tool steels. This process was announced at the close of the nineteenth century, and the results of the Taylor-White process were demonstrated on a large scale at the Paris Exposition in 1900.

Notwithstanding the fact that the originators of this process took a special trouble to disclaim the invention of a steel, but only a process for treating steel, a large number of workers in steel still seem to feel that they were the inventors of the product known as "High Speed Steel." Mr. Taylor, in his epoch-making paper on the "Art of Cutting Metals," very plainly states that this was not the case, and most users of steel have forgotten that the type of steel to which this treatment was first applied was the high-carbon air-hardening steel used prior to 1900.

The change from air-hardening to high speed steels was rather a matter of evolution than a distinct invention, and I have not been able to ascertain that the change was the result of any one man's discovery or invention. Chemically speaking, the change consisted in a very radical lowering of the carbon content and a great increase in the tungsten or molybdenum content. The chromium percentages have not been materially altered as compared with previously existing air-hardening steels; but high manganese, which was an important constituent of the original Mushet steel, is not now an important constituent in high speed steel; in fact, chromium replaced manganese in most of the air-hardening steels during the later years of their use in the nineties.

In 1901 the writer collected a number of the typical analyses of air or self-hardening steels from large users of these products. In 1902 our analyses showed that the change had already taken place in America, England and Germany, and the contrast is illustrated in Tables I and II. Each table contains products of the three countries mentioned, but the exact maker is not designated.

The high carbon content and the low tungsten or molybdenum content in Table I indicates the character of air-hardening steels in use prior to 1901.

In Table II, although these analyses were made only one year later, it is seen that a change in character has come about, and relatively low carbon, with high tungsten or molybdenum, is the characteristic feature of the new steels. It will be noted that two of the steels in Table II, one a molybdenum and the other a tungsten steel, contain no chromium.

It should be borne in mind that during the later days of air-hardening steels and the earlier days of high speed steels, it was a difficult matter to produce low carbons with the available ferro-alloys. The introduction of electric furnace and alumino-thermic alloys had much to do with the success of manufacturers in keeping their carbons down, but the idea that they should be reduced and that the alloys might be increased in conjunction with the application of a high heat treatment seems to have been almost spontaneous with the makers of tool steel in every country. In my search for the definite origin of this idea I learned of a user of steel who in the early days of the Taylor-White process obtained some extraordinary results with a particular bar of the old Sanderson self-hardening steel. Upon analysis it developed that this particular bar was considerably lower in carbon than usual, and instead of reporting this fact to the maker, he gave a sample of the steel to the representative of a foreign mill. My former associate at the Sanderson Works, Dr. E. L. French, is on record, however, as having predicted prior to 1900 that the tendency would be to rely for hardening upon tungsten and chromium rather than upon carbon in order to secure the kind of hardness which

TABLE I.—SELF-HARDENING STEELS, 1901.

Maker No.	Carbon, per cent.	Manganese, per cent.	Chromium, per cent.	Tungsten, per cent.	Molybdenum, per cent.
1	2.19	1.32	0.50	5.63	....
2	1.69	0.45	3.73	7.63	....
3	1.14	0.33	2.09	7.98	....
4	1.79	0.50	3.96	....	4.54
5	1.55	0.24	3.22	7.80	....
6	1.55	0.21	3.67	9.42	1.10
7	1.78	1.18	....	7.22	....
8	1.40	1.65	3.69	....	4.59
9	1.75	3.92	....	6.61	....

TABLE II.—HIGH SPEED STEELS, 1902.

Maker No.	Carbon, per cent.	Manganese, per cent.	Chromium, per cent.	Tungsten, per cent.	Molybdenum, per cent.
21	0.63	....	4.00	.....	6.00
2	0.42	....	4.95	10.75	....
23	0.57	0.43	3.30	11.58	....
24	0.75	....	....	19.50	....
25	0.37	....	5.10	13.83	....
26	0.62	....	6.50	21.06	....
27	0.84	0.07	2.76	11.25	....
28	0.56	....	2.95	9.74	....
29	0.60	0.30	....	.....	9.25

resists tempering—in other words, the peculiar red hardness upon which high speed steels depend.

It is probable that we shall never know who took the radical step and made the first low-carbon, high-tungsten high speed steel, but immediately following the announcement of the Taylor-White process there was great activity on the part of all tool steel makers in every country to produce a product which would yield maximum results when treated by this process. The Courts decided that Messrs. Taylor and White did not make a patentable invention or discovery. A world jury, however, seemed to differ with this decision and every scientific honor was awarded them for their epoch-making announcement which revolutionized machine-shop operation and machine-tool building.

With the development of high speed steels there has been much study devoted to them from many angles. The engineer, the machinist, the chemist and the metallurgist have all been interested, and much has been said and written in regard to this remarkable product. The question to be answered by all investigators of high speed steels has been: What constitutes the most efficient cutting tool and why? In Mr. Taylor's work "The Art of Cutting Metals," the point of view of the machine shop economist is most ably presented. His work records the development of a high speed tool in regard to its composition, its heat treatment and the method used to secure the most economical removal of metal. The peculiar property of these steels in resisting softening in use Mr. Taylor has called the "quality of red hardness," and he makes no attempt to connect red hardness with any of the previously known physical properties of metal. The only method of measuring this quality of red hardness known to Mr. Taylor was the very expensive and time-consuming resort to cutting tests. The necessity for shorter and more easily applied tests was appreciated by Mr. Taylor, for he says, referring to cutting tests: "This test requires so much expensive apparatus, consumes so much time and is so slow, that a simpler index or guide which will indicate correctly the quality of high speed tools is much needed. Moreover, we firmly believe that in time some simpler index to the property of red hardness in tools will be found."

Accepting this suggestion, many able scientists have conducted investigations upon the hardening and tempering qualities of high speed steels of many compositions, and also in connection with the study of the specific functions of the various elements entering into their composition. A short bibliography of the leading articles will be found at the close of this paper. I might mention specifically the work of Dr. H. C. H. Carpenter upon the types of steel and critical ranges of heating and cooling of high speed steels under varying thermal treatment, and also upon the tempering and cutting tests of high speed steels. The writer took a special interest in these investigations because of the fact that he had the pleasure of furnishing Dr. Carpenter many of the alloys used by him, taken from materials used in his early investigations in this country.

It may be taken for granted that any one interested in the scientific study of high speed steel will study Mr. Frederick W. Taylor's work upon the art of cutting metals. Dr. C. A. Edwards has studied the function of chromium and tungsten in high speed steels, and in conjunction with Mr. H. Kikkawa, published a later paper upon the effect of chromium and tungsten upon the hardening and tempering of high speed tool steel. Particular attention should also be given to the papers by Prof. J. O. Arnold and A. A. Read upon the chemical and mechanical relations of iron and carbon when associated with tungsten, molybdenum, chromium and vanadium. Each of these elements has been taken up one at a time in its relation with iron and carbon.

Dr. Carpenter, in studying the heating and cooling curves of tungsten and molybdenum products, finds the effect of these elements to be, first, the widening, splitting and lowering of the critical ranges by the special alloy elements; second, the complete suppression of the widened, split and lowered range by rapid quenching. He found also that these steels so hardened were in the austenitic condition and showed no signs of tempering when reheated below 500° C. and in some cases to even higher temperatures. Carbon tool steels show the effects of tempering as low as 200° C. Dr. Carpenter later supplemented this investigation with another one in which he studied the effect of etching reagents upon hardened and tempered high speed steels as prepared for microscopic examination. In general he found that the higher the steel had been heated for hardening, the less slowly it was attacked by the etching reagent. Also that when fully hardened and later subjected to tempering operations, the converse was true, namely that the more fully the temper had been drawn the more easily it was attacked by the etching material.

Dr. Edwards, in his earlier paper, finds that hardness assists the efficiency of the cutting tool, referring to purely mineralogical hardness as distinguished from red hardness. He also states that chromium forms a double carbide with tungsten and a new brittle constituent appears at about 700° C. in tempering which caused the failure of high speed tools. In his later statement, published jointly with Mr. Kikkawa, he abandons these last two positions but states that chromium in these steels in conjunction with carbon is the cause of the great hardness of high speed steels and that it produces a marked lowering in the temperature at which hardness can be effected. He differs with the earlier conclusions of Dr. Carpenter that chromium does not confer the quality of air hardening in the absence of tungsten or molybdenum, but that chromium steel so hardened in air develops a comparatively slight degree of secondary hardening or "red hardness," as Taylor designated it.

In regard to high tungsten steel in the absence of chromium, he finds that a large proportion of the tungsten remains undissolved even when the temperature is raised to the melting point, and agrees with Arnold and Read that this tungsten is probably in the form of a tungsten iron compound, Fe_2W. Very rapid quenching from high temperatures results in much less hardening than is obtained from a high chromium steel similarly treated; but the tungsten steel, on tempering, undergoes a very pronounced secondary hardening—in other words, it is the tungsten which confers the quality of red hardness. While Dr. Edwards, in his investigation, did not cover a study of molybdenum, we can say that molybdenum in its effects is very closely analogous to tungsten and about twice as efficient; that is, an amount of molybdenum confers a degree of red hardness similar to or greater than twice its weight of tungsten. The difference between these two metals seems to be one of degree rather than of kind. When chromium and tungsten are present together the presence of the chromium increases the solubility of the tungsten when raised to high temperatures. Dr. Edwards states that the maximum of resistance to tempering and the greatest degree of secondary or red hardness is obtained by getting the tungsten into complete solution, and in modern high speed steels he places this temperature at about 1350° C. (2462° F.). In our experience this temperature is too high for practical results and is apt to result in brittleness, and also, as will be shown later, the hardness seems to decrease rather than increase upon extreme over-heating to such a temperature, and at this temperature there is formed a so-called "brittle constituent," to which Dr. Edwards refers in his first paper. This constituent is due solely to over-heating and is not produced when tempering at 700° C. (1392° F.) in properly hardened high speed steel.

Dr. Edwards also points out very clearly, and shows by his results, that this secondary hardness by drawing the temper may be and usually is actually greater than the initial hardness of the hardened high speed before the temper has been drawn at all, but that at intermediate drawing temperatures there is some lowering of the hardness, which later increases as we approach the temperature at which full annealing begins. The temperature at which he finds the maximum secondary red hardness coincides almost exactly with the temperature given by Taylor as that recommended for the second heat treatment required in the Taylor-White process, for, as described by Mr. Taylor himself, the second heating of the hardened tool consists of heating the tools "(*a*) to a temperature below 671° C. (1240° F.), preferably to 621° C. (1150° F.) for about five minutes; (*b*) cooling to the temperature of the air either rapidly or slowly."

As previously reported to this Society, in a paper entitled "Magnetic Habits of Alloy Steels,"[1] the writer began some fifteen years ago to study systematically, and as a matter of routine, the magnetic properties of practically all the alloy steels manufactured in our regular line of business. That paper did not touch upon any magnetic work in conjunction with air-hardening or high speed steels, but such work was commenced in the earliest days of the modern high speed steel, and renewed attention was given to this matter after the suggestion of Mr. Taylor that a simpler index or guide to the quality of high speed steels would be of great use and importance. A paper on the subject of the physical characteristics of high speed steel was promised for presentation at the last meeting of the International Association for Testing Materials held in New York in 1912. At that time the work was not sufficiently advanced to permit of presenting the results, and, in fact, even yet the results are not what we had hoped to obtain from this long continued study. It was thought that there might be found some critical temperatures in connection with the magnetic or electrical resistance of high speed steel which would furnish a definite indication of its properties at those temperatures most suitable for commercial hardening. In addition to magnetic and resistance tests of various high speed steels hardened and tempered in a wide variety of ways, we have supplemented the work with microscopic examinations, and to some extent by cutting tests.

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[1] *Proceedings*, Vol. XIV, Part II, p. 50 (1914).

While in the aggregate a great variety of high speed steel compositions have been tested, not only of our own regular and experimental steels, but also commercial steels of a great many brands foreign and domestic, the greater part of the systematic investigation was confined to four steels, the analyses of which are given in Table III. These steels cover quite a range as regards their chromium, tungsten and vanadium content. Steel No. 31 represents a type which was fairly generally used about ten years ago; in fact various writers, as the result of practical tests, have contended that tungsten above 13 or 14 per cent is of no advantage. Practical experience, however, has led for the most part to higher tungsten percentages.

Steel No. 34 is introduced because it corresponds quite nearly with the analysis of steel to which Mr. Taylor referred as giving the best results obtained with any steel at the time he was actively engaged in this work. In fact, because of Mr. Taylor's recommendation, steel of this character was once adopted as the standard material desired by the Navy. Their specification, however, calling for high tungsten and high chromium, was abandoned after one year because it was found that steel of the type represented by No. 33 gave materially better results.

Steel No. 32 is intermediate in quality as compared with Nos. 31 and 33. As the result of a very exhaustive series of cutting tests made as nearly as possible in accordance with the methods outlined and recommended by Mr. Taylor, these four steels will rank about as follows, starting with No. 33 as 100 per cent efficient: Steel No. 34 would be represented by 70 per cent, No. 32 by 66 per cent and No. 31 by 45 per cent.

It is apparent, therefore, not only from the analysis but from the figures above, that the steels are typical of well-known commercial types of steels, and it therefore might be thought that their behavior electrically and magnetically, also as to hardness, would show marked differences, with possibly some differences in critical temperatures both in hardening and in drawing. However, this does not appear to be the case, but the following general conclusions can be stated in regard to all of them.

TABLE III.—ANALYSES OF FOUR STEELS USED IN TESTS.

Steel No.	Carbon, per cent.	Silicon, per cent.	Manganese, per cent.	Chromium, per cent.	Tungsten, per cent.	Vanadium, per cent.
31	0.63	0.19	0.26	4.21	13.10	0.25
32	0.61	0.19	0.36	3.34	16.28	0.40
33	0.63	0.27	0.31	2.99	16.87	0.85
34	0.64	0.22	0.24	5.35	18.99	0.15

Starting with hardening temperatures at 982° C. (1800° F.) and carrying them up to 1315° C. (2400° F.), it would be noted that the electrical resistance, the scleroscope hardness and the coercive force increase fairly uniformly with the hardening temperature up to about 1260° C. (2300° F.). There is a slight tendency to show a reversal of these properties beyond this temperature. In other words, it would indicate that overheating had commenced. Magnetic induction and residual density, as the hardening temperature increases, are lowered.

If these steels hardened at proper temperatures to develop full austenitic structure are subjected to the tempering operation varying from room temperature up to 649° C. (1200° F.), it is noted that there is a general falling off in the hardness, resistance and coercive force as the drawing temperature is increased. This is not quite in accord with statements that have been made that there is no effect in drawing the temper of high speed steel until the temperature of 500° C. (932° F.) has been reached. It is true, however, that the effect upon these properties is only slightly influenced below this temperature, while the rate of change increases fairly rapidly at temperatures above 482° C. (900° F.). There is no indication, as regards magnetic properties, of anything corresponding to the secondary hardening referred to by Edwards, nor have we found it in connection with hardness tests made by the scleroscope. In cases where the Brinell method is used we found it very difficult to get constant results with materials so extremely hard, but with that method we have found an indication of re-hardening, or secondary hardening at high drawing temperatures, the maximum usually being at about 593° C. (1100° F.). The lower the temperature at which the initial hardening is done the lower will be the temperature at which the re-hardening occurs on tempering, and presumably the sooner a tool so treated would fail in severe cutting where the frictional temperature was high. When the temperature in cutting is not extremely high we cannot conclude that the steel would fail sooner than one with a higher rehardening temperature. In such cases, in my opinion, physical or mineralogical hardness plays an important part as distinguished from red hardness, but where the cutting conditions are severe it would appear logical that the higher the temperature of red hardening the longer the endurance of the tools.

The tests that we have made were for the most part made upon hot rolled 1 by $\frac{5}{8}$-in. bars in just the condition that might have been used for cutting tests or for supplying to users. After all heat treatments, however, the surface was examined by file testing to see that no unreasonable decarbonization had taken place. There was, however, some slight decarbonization of surface in all cases, undoubtedly due to scale and oxidation. However, we wished to operate under conditions as nearly as possible those that would obtain in practical work in case it were found possible to make use of physical tests rather than cutting tests as a means of judging the relative merits of high speed steels. Of course for determining hardness it is necessary to remove, by grinding, sufficient material to get below any possible decarbonized or oxidized zone.

We are convinced that to make these tests with scientific accuracy would require conditions of heating and temperature control much more refined than are usually found in industrial plants and that it would be desirable to operate on round pieces which could readily be rough turned prior to any treatment and ground on centers after each treatment to insure making the test on perfectly sound material. This, in my judgment, removes such methods from the kind of tests that Mr. Taylor had in mind, as they introduce the same element of expense and require the expenditure of considerable time.

For purely scientific reasons it might be worth while to conduct such a series of tests on different types of high speed steel; the intervals of temperature should preferably be not over 28° C. (50° F.) both in the tests made on hardened bars and also on the tempering ranges, particularly from, say, 482° C. (900° F.) up to the point of softening. This is entirely too complicated and extensive a program to consider as a convenient substitute for the cutting tests.

To refer again to the title of the paper and what is meant by "Modern," we might call attention to the difference in analyses displayed in Tables II and III. The most noteworthy change is in the introduction of vanadium, which is now used in practically every high speed steel; in fact, it is the only general addition that has been made to the earlier types which seems to afford universal improvement in quality. The writer began experimenting with the use of vanadium in 1903, and it is well to bear in mind that at that time vanadium was almost a chemical curiosity. It was worth about $15.00 a pound, and this was some time prior to the formation of the American Vanadium Co. which manufactured and sold vanadium in large quantities. So far as the writer is aware, the entire stock of ferro-vanadium in the country when these experiments were begun consisted of not over 100 lb. in the hands of two different dealers in New York. We purchased one-half of the entire stock of each dealer. As the result of these experiments carried on at the old Sanderson Works, a patent was granted the writer, issued on January 3, 1905. Other experimenters were doubtless working with the same thing, and, in fact Mr. Gledhill referred to its use in 1904, as did also Mr. Taylor. In fact, the composition of tool steel previously referred to as giving Mr. Taylor his best results, showed 0.3 per cent of vanadium. During the year 1905 the Rex AA steel was put upon the market, and other vanadium steels followed shortly, but it was not until three years later that certain foreign makers copied this original steel exactly and made great claims as to originality in regard to their product.

As has been stated, vanadium seems to have conferred general benefit upon all tungsten-chrome or molybdenum-chrome high speed steels. In this particular it differs from other additions that have been introduced since. The use of cobalt received considerable attention a few years ago, but it was noted that it was always present as an addition to types of steels that would have given remarkably good results if the cobalt had been omitted. I have never seen anything to indicate that it could be used as a substitute for any of the other elements regularly present, and its use is not now as extensive as it was a few years ago. As an element of increased cost it has not shown sufficient improvement in the long run to warrant its general use. So far as our observations are concerned it seems to lead to some uncertainty in the manufacture and treatment of the steel, and steels containing it seem to be more difficult to re-forge or re-dress than steels in which it is absent. These comments are made notwithstanding the fact that one of the most carefully conducted competitive tests on high speed steel ever made in an industrial plant was won by a steel containing cobalt, and it might be added that there is every probability that the same steel without the cobalt would have been equally successful.

The use of uranium has been advocated during the past few years, but it seems to be very difficult to handle owing to the ease with which it is oxidized, and so far as our experience goes we have been unable to see that it confers any specific benefit. Such steel as we have examined has been more apt to show seams and surface defects than steel in which it is absent, and the microstructure of the steel itself usually indicates the presence of considerable amounts of material that are suspected of being oxides of uranium. It should be noted that when oxide of uranium is formed in melting it has small chance of being eliminated in the slag owing to its great weight. It may be that with more experience means will be found of introducing this material into the bath without such great loss of expensive metal and without the formation of these impurities in the steel which cannot but prove detrimental.[1]

Other elements have been tried, including cerium and zirconium, but no conclusions are available as yet.

The term "Modern" High Speed Steel therefore may be considered as referring to the product since the introduction of vanadium, as no generally accepted improvement has been made in high speed steel since that time. Improvements have resulted in the general quality of the material available, due to greater skill in manufacture, and to the availability of superior raw materials in the form of metals and ferro-alloys than were obtainable in the early days of the industry. It is still a constant source of surprise to see tests conducted in which a steel that may appear of inferior analysis proves successful, whereas some other type of analysis, judged from this viewpoint only, would naturally be expected to prove the better steel. In a very elaborate series of tests, including over 50 analyses, it was noted that in those steels included in the first group as to merit the compositions vary from 12.70 to 18.59 per cent of tungsten, from 1.70 to 5.58 per cent of chromium, from 0.40 to 1.73 per cent of vanadium, and from 0.52 to 0.81 per cent of carbon. The steels rated as second and third class in general covered almost identical ranges. It therefore seems that steel making rather than chemical analysis is the first consideration, and so far we are not able to define or to specify all the elements which enter in, from the melting to the finishing of a bar, to produce first-class material in a very wide range of analyses, and no physical or chemical test has as yet been developed which helps very much in determining the matter of quality.

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[1] Since the above was written there has been put on the market a very low carbon high uranium content Ferro-Uranium. This, it is believed, will be more successful than the high carbon Ferro-Uranium originally available.

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DISCUSSION.

Mr. Kelley.

MR. GEORGE L. KELLY (*presented in written form*).—Mr. Mathews has clearly indicated the difficulties in the way of determining the best composition and treatment for high speed steel. All of us have made and treated certain compositions which in their performance in preliminary tests seemed likely to exceed our expectations, only to have them fail in the final tests. The performance of high speed tools is dependent upon so many factors that this is not altogether astonishing, yet in the last resort the value of the material is in proportion to its good behavior in the cutting test. Mr. Mathews will have made an extremely valuable contribution to the testing of high speed steels if his work on magnetic testing of these steels will permit us to predict the performance of a given steel. Its value will be even greater if it indicates why the tested specimen will succeed or fail. But such a test will not be generally accepted until a large amount of work by several investigators has definitely established the connection between the magnetic tests and the performance in the shops.

The cutting test contains so many variables that great care must be taken that some of these, inadvertently introduced, do not lead to wrong impressions concerning the performance of the tool. Uniformity of conditions in grinding the tools and operating the testing lathes are as important as the composition and treatment. On the other hand we must maintain a certain degree of correspondence with shop conditions, for the object is to determine the value of the material for shop use. The writer recalls one instance of a composition which under test unquestionably surpassed the next best composition, but when this was tested on general work in the shop, it failed so completely that no large class of operations was found among many varieties where it could be used to advantage. This indicates the importance of closely copying the best of shop practices in a test, and of even actually testing the material in the shop before finally accepting the result of the quantitative lathe test. Such a test, of course, should include a series of compositions representing

Mr. Kelley. a range of carbon with the other elements as nearly constant as practicable.

Leaving for the moment the question of the test and considering the question of composition, we again find a large amount of evidence which indicates the difficulty in the way of drawing dependable conclusions. Mr. Mathews has pointed out that the best and poorest tools often fail within the same ranges of composition. In general, the experience at the Nicetown Plant of the Midvale Steel and Ordnance Co. is in harmony with that which he has expressed. I might add that we hold a decidedly better opinion of cobalt high speed steels. As to tungsten, we have reached the conclusion that no advantage accrues from using a high content of tungsten. Fourteen per cent seems to us to give as good results as higher percentages. We have not tried cerium and zirconium in high speed steels, elements which Mr. Mathews mentions, but we have tried tantalum. From its position in the periodic table, this might be expected to show effects similar to those of vanadium. Our experiments so far, however, have not shown any advantage to attend its use. Sulfur is an element which Mr. Mathews left out of his discussion, and probably he would be willing to leave it out of the steel, too, if that might be brought about. According to Arnold, sulfur in quantities up to 0.10 per cent is not harmful. We made a series of experiments with the object of bringing out the effect of this element. Our conclusions were not in agreement with those of Arnold in that we did find the cutting power of the steel to be reduced by high sulfur. The effect, however, did not appear to be serious until the amount of sulfur exceeded 0.06 per cent.

The so-called sweating operation is undoubtedly one of the most important steps in producing a good cutting tool. We have conducted experiments in which tools were placed in a furnace at constant temperature for various lengths of time. As a result of these experiments it appeared that a temperature of 2350° F. for times under five minutes gave the best results, and that a temperature of 2300° F. gave excellent results when the times were longer up to 30 minutes. Beyond 30 minutes there was a falling off in cutting efficiency. The difficulty of standardizing such treatment, involving as it does factors of heat conductivity, heat capacity and time, is considerable. Small pieces of steel,

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which are placed entirely in the furnace and which can be allowed to reach the temperature of the furnace, can be controlled satisfactorily; but larger lathe tools, which are hardened only on the end, cannot be reliably heated either by immersing the tip of the tool in a salt bath, or by inserting one end in a furnace. We have had some success in placing tools in a furnace considerably above the desired temperature and observing the temperature of the steel itself with an optical pyrometer. However, the difficulties in the way of reading such temperatures satisfactorily, and of determining what temperature allowance to make for differences in size, are great in experimental work, and almost insuperable in practical work.

Mr. Mathews quite properly reduces the problem to one of steel-making. Improvement in steel-making must begin with the raw material and continue through the melting and casting. Even here the care may not end, but must follow the material at every stage of its manufacture into the ground tool.

Mr. Parker.

MR. J. H. PARKER (*presented in written form*).—The speaker has read with a great deal of interest this paper on "Modern High Speed Steel," and would like to discuss several features of it.

As regards the addition of vanadium to the earlier tungsten-chrome high speed steel, it is interesting to note that a vanadium content up to 2.50 per cent has been used very successfully in connection with a lowering of the tungsten content to approximately 12.50 per cent. The red-hard condition, following proper treatment, is increased and in certain types of work, notably dry cutting, increased efficiency has been obtained. This has been demonstrated in the last three or four Navy tests as compared with the steels of the No. 33 type given in Table III of the paper. In carrying the tungsten and vanadium contents still higher till we have a steel approximately:

Carbon	0.60	per cent
Chromium	3.00	"
Tungsten	20.00	"
Vanadium	4.50	"

the peak of red-hardness has been passed to such an extent that a steel of this analysis will not harden, even when quenched in water from temperatures varying from 2300° down to 1400° F.

Mr. Parker. Just where the peak of this tungsten-vanadium combination is the speaker has not definitely determined.

In regard to the use of cobalt, the speaker agrees with the author in a general way, but with one reservation. The addition of cobalt up to 5.00 per cent—that is, adding up to 5.00 per cent cobalt to the other elements regularly present in recognized high speed steels—has a neutral action. Extensive tests were carried out by the speaker several years ago in which three standard types of high speed steel were used, and to these standard analyses were added from 1.00 to 5.00 per cent of cobalt. Actual cutting tests were made in each case, and there was no difference in efficiency between steels of similar analysis, whether the cobalt was present or not. If, however, a considerable percentage of cobalt is added,—not in a general way as an alloying element to affect the iron base, but rather replacing the iron and thereby having the cobalt-iron base affecting the carbon, chromium, tungsten and vanadium usually present,—a marked increase in cutting efficiency has been found. Cobalt is added to produce a base having approximately the formula Fe_2 Co, and this, in a general way, corresponds to approximately 28 per cent of the whole alloy being cobalt. This is covered by a patent granted the speaker and B. H. DeLong, issued July 10, 1917.

In regard to the author's discussion of high drawing temperatures and the secondary hardening resulting therefrom, it has been the speaker's experience that a true secondary hardening does not occur at high drawing temperatures, such as 1100° F., unless the high speed steel tool has been heated to a sufficiently high temperature in hardening. If we assume a correct hardening temperature of 2250° F., and harden a tool from this temperature or from a temperature a little higher, then secondary hardening will be accomplished by a high drawing temperature, at say approximately 1100° F. If, however, the tool is hardened from 2100° F., then the effect of drawing temperatures on high speed steels is more nearly like that of simple carbon steels; only, of course, higher drawing temperatures are required to produce similar results. In the speaker's experience with the hypothetical case under discussion, the tool hardened from 2100° F. will not do as good work as the tool hardened from 2250° F., regardless of the drawing temperature and regardless of the temperature of

Mr. Parker. the tool at work, that is, whether it is used dry or whether it is used wet with a large amount of cutting compound which keeps the cutting edge of the tool relatively cold. Makers of high speed tools as a class do not develop in the high speed steel tools all the potentialities that the steel possesses, because they are afraid of ruining the cutting edges of the tool by using the high temperatures necessary to secure proper initial hardening. To turn out formed tools with the proper initial hardness requires carefully regulated furnace conditions, and a high degree of skill on the part of the tool hardener, but it can be and is being done.

The speaker believes that the author's definition of the term "modern" high speed steel should be accepted as generally correct. It is interesting, however, to find a number of cases even to-day where some of the "older" high speed steel types work out to better advantage than the "modern" ones, that is, those containing vanadium; but from the standpoint of red-hardness the "modern" steels are undoubtedly superior.

In conclusion, the speaker desires to concur with the author in that steel-making, rather than chemical analysis, is the first consideration. Some buyers of high speed steel insist on certain analysis, usually specifying a tungsten content only. The speaker does not believe that chemical specifications for high speed steels are of any avail to the consumer, for in high speed steel more than any other alloy steel with which the speaker is familiar, there are so very many points of merit not covered by the analysis.

Capt. Baxter. BUREAU OF CONSTRUCTION AND REPAIR, U. S. N.; CAPT. W. J. BAXTER (*presented in written form*).—The paper offered by Mr. Mathews is an excellent brief exposition and résumé of the subject of tungsten high speed tool steel. The Bureau notes, however, that Mr. Mathews has not attempted to cover any of the tungstenless high speed steels; and as the Navy has recently considered one such steel at least, which, so far as the Bureau is aware, has not been investigated and reported upon in this country heretofore, the Bureau is pleased to submit for such information as they may be worth, the following data obtained as a result of three separate investigations conducted by the Navy.

Lt. S. E. Woodworth, U. S. N., attached to the Bureau of Ordnance, Navy Department, Washington, D. C., obtained upon

Capt. Baxter. the occasion of a recent visit to the Darwin & Milner Tool Steel Mills in Sheffield, England, a quantity of a comparatively new kind of high speed tool steel known as "cobaltcrom." Lieutenant Woodworth upon his return to this country undertook to have the material in question investigated in comparison with some of the usual brands of tungsten high speed steels. The data obtained have been placed at the disposition of the Bureau of Construction and Repair, and in offering this discussion the Bureau desires to give the credit for the data to the Bureau of Ordnance, and in particular to Lieutenant Woodworth of that Bureau.

Cobaltcrom in the form of a $\frac{7}{8}$-in. octagon forged bar (sample A-141) and a 4-in. diameter, $\frac{1}{4}$-in. thick cast milling cutter (sample A-142) was subjected to one series of tests conducted at the Brooklyn Navy Yard by Dr. Wm. Campbell, Consulting Metallurgist of that Navy Yard. The chemical analysis of sample A-141 showed the following:

Carbon	1.48	per cent
Manganese	0.19	"
Silicon	0.80	"
Chromium	13.57	"
Cobalt	3.66	"
Molybdenum	0.84	"

Hardness determinations were made on samples from both A-141 and A-142, the samples being heated to various temperatures in a small electric furnace, one piece being quenched in oil and another cooled in air. Tables I and II summarize the hardness data obtained for the forged and cast material. Table I for the forged metal shows that hardening begins about 850° C. and reaches a maximum at 1000° C., the hardness being practically the same whether the material is cooled in air or oil; while Table II for the cast metal shows slightly higher values, with a maximum at 1000° C. as is the case for the forged metal.

The microstructure of the forged bar (sample A-141) is shown in Figs. 1 to 3 inclusive. Summarizing the results of the micro-examination of the forged metal, it may be stated that the metal as received consists of carbide in the form of irregular patches and globules surrounded by very fine pearlite. The

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carbide is somewhat segregated and follows the outline of the original dendrites, which are more or less drawn out by the forging. Above 850° C. the structure of the oil-quenched and air-cooled samples is practically the same and consists of martensite of very fine texture containing tiny patches of carbide generally with a dendritic arrangement; that is to say, the aggregation of carbide forms the matrix to the dendrites of martensite. The structure is practically the same after the maximum temperature of quenching.

TABLE I.—FORGED METAL (A-141).

Specimen.	Temperature.	Brinell Hardness (3000 kg.).
A-141	As received.	245
A-141-2	825° C. Oil.	248
A-141-3	855° C. "	512
A-141-4	900° C. "	555
A-141-5	1000° C. "	654
A-141-6	850° C. Air Cooled	477
A-141-9	900° C. " "	532
A-141-7	950° C. " "	589
A-141-10	975° C. " "	614
A-141-8	1000° C. " "	652
A-141-11	1025° C. " "	652
A-141-12	1050° C. " "	644, 622, 635 or 647

TABLE II.—CAST METAL (A-142).

Specimen.	Temperature.	Brinell Hardness.
A-142	As received	342 (1500 kg.)
A-142	825° C. Oil	473 "
A-142-3	855° C. "	578 (3000 kg.)
A-142-6 (*d*)	900° C. "	589 "
A-142-5	1000° C. "	698 "
A-142-18	850° C. Air Cooled	544 "
A-142-16	900° C. " "	600 "
A-142-7	950° C. " "	640 "
A-142-15	1000° C. " "	683 "
A-142-19	1050° C. " "	652 "

The microstructure of the cast metal (sample A-142) is illustrated in Figs. 4 to 8 inclusive. Summarizing, it may be stated that the structure of the metal as cast is finely dendritic. The size of the dendrites varies with the thickness of the section. These dendrites are surrounded by a matrix of the carbide eutectic. Some of them are undoubtedly pearlitic, while some may be martensite because the metal is comparatively hard to

FIG. 1.—As Received in Annealed Condition.

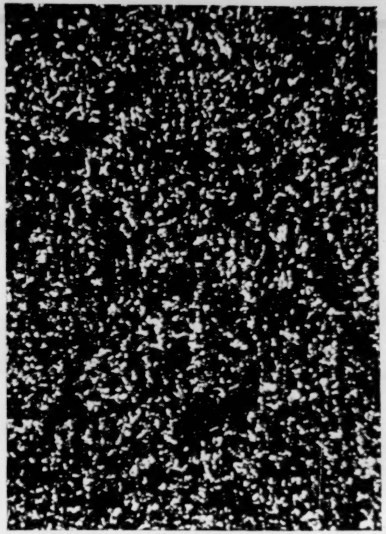

FIG. 2.—Heated to 1000° C. and Quenched in Oil.

FIG. 3.—Heated to 1050° C. and Cooled in Air.

FIG. 1.—The matrix is very fine-grained pearlite containing light hard dots of carbide more or less strung out in lines. These lines of carbide are the remains for the most part of the carbide eutectic of the original casting.

FIG. 2.—The section is deeply etched and shows the strings of carbide in cross-section. The remains of the old dentritic structure can be seen. The matrix is no longer pearlitic but is hard.

FIG. 3.—The structure is similar to that shown in Fig. 2 but the carbide is somewhat finer; this may be due to the fact that the matrix has absorbed more carbide than in Fig. 2, but it may be due to a difference in texture in different parts of the bar.

LONGITUDINAL SECTION OF FORGED BAR. ETCHING, PICRIC ACID (× 100).

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cut with a saw. The samples heated to various temperatures and cooled in oil or air show, as might be expected, no change in the dendritic structure. The dendrites, however, change from pearlitic to martensitic, and at higher temperatures it would seem that some of the carbide is absorbed by the dendrites.

In a second investigation, cast and forged cobaltcrom high speed tools were submitted to comparative tests with tungsten high speed tools, the tests in question being made at the Bureau of Standards, Washington. The cobaltcrom tools thus tested were as follows:

SAMPLE NO.	MATERIAL.
1 and 2	2 cast milling cutters 4 in. in diameter and $\frac{1}{4}$ in. thick.
3	1 cast milling cutter $3\frac{3}{4}$ in. in diameter, $\frac{1}{8}$-in. teeth staggered.
4	1 cast milling cutter 3 in. in diameter, $\frac{3}{8}$ in. thick.
5	1 Hack saw blade, 12 by $\frac{1}{2}$ by 0.032 in., 14 teeth per inch.
6	1 Forged octagon bar 9 in. long, $\frac{7}{8}$ in. thick.
7	1 Forged lathe tool $\frac{5}{8}$ in. square; this tool was cut in half and made into two tools marked No. 7 and No. 7*a*.

Samples Nos. 1, 2 and 4 were sent to the Washington Navy Yard for grinding. Cutting tests were made at that Navy Yard on samples Nos. 1 and 4, while sample No. 2 was returned to the Bureau of Standards for heat treatment preliminary to a cutting test at the Washington Navy Yard. The heat treatment given this sample was an air-cooling from 1030° C., until black, followed by quenching in oil.

Sample No. 3 was broken up for the study of the effect of the temperature and the period of annealing on its microstructure.

Sample No. 5 was tested at the Bureau of Standards in comparison with a tungsten "Star" hack saw blade.

Sample No. 6 was cut into disks about $\frac{1}{8}$ in. thick and the effect of hardening temperature and reheating temperature on their scleroscope hardness was determined as an indication of

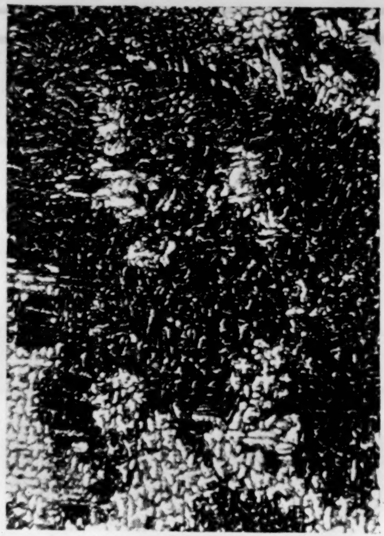

FIG. 4.—As Cast, near Edge of Tooth.

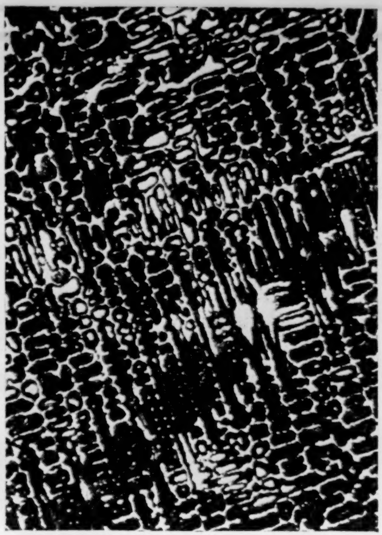

FIG. 5.—Web of Tooth.

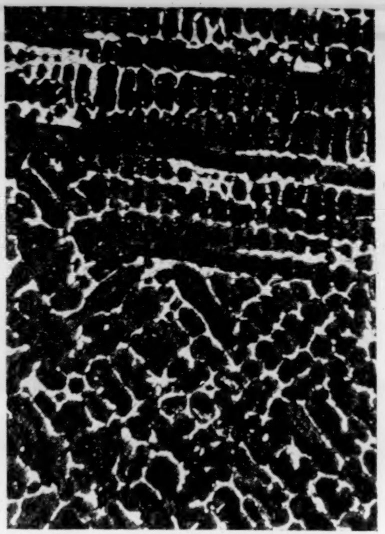

FIG. 6.—Edge of Tooth; Heated to 900° C. and Quenched in Oil.

FIG. 4.—The structure is finely dendritic. Some of the dendrites etch light and some dark. There is a fine network of the carbide eutectic evenly distributed.

FIG. 5.—The texture is somewhat coarser and the light etching areas or cores of the dendrites are greatly reduced in amount. The matrix or eutectic shows up very distinctly. This part of the section cuts readily with a hack saw.

FIG. 6.—The dendritic structure is coarser than in Figs. 4 and 5 but this is due to the original casting having frozen more slowly and is not the effect of reheating. The dendrites now etch uniformly and are hard. The carbide eutectic shows up as a matrix as before.

CROSS-SECTION OF CAST TOOTH. ETCHING, PICRIC ACID (× 100).

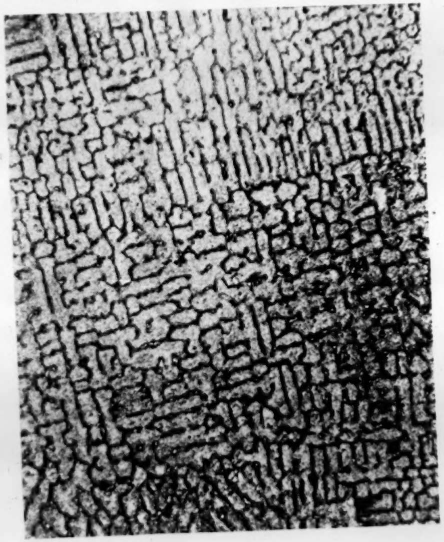

FIG. 7.—Web of Tooth; Heated to 1000° C. and Cooled in Air. Light Etch.

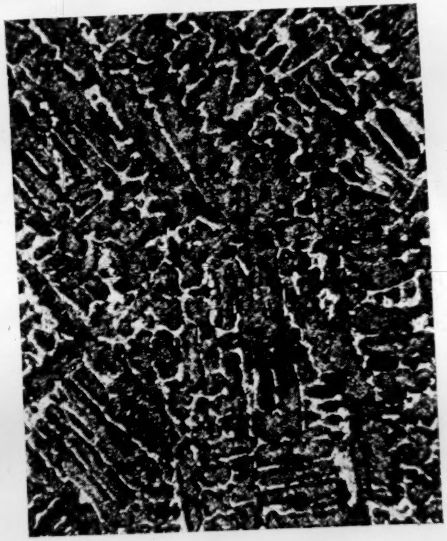

FIG. 8.—Hub; Deeper Etch.

FIG. 7.—The dendritic structure is comparatively fine. The amount of carbide eutectic is materially less, as if absorption had taken place.

FIG. 8.—The photograph shows the structure of the hub, which being thicker than the web has a coarser structure. The dendritic pattern is, therefore, much coarser than in Fig. 7. Compared with Fig. 6, the amount of carbide eutectic has decreased, which seems to indicate absorption of carbide by the unsaturated dendrites.

CROSS-SECTION OF CAST TOOTH. ETCHING, PICRIC ACID (× 100).

Capt. Baxter. the best heat-treating temperatures of this material and to compare it with tungsten high speed steel.

Samples Nos. 7 and 7*a* were given a cutting test in a lathe in conjunction with a tungsten high speed lathe tool.

Thermal curves of material similar in composition to that under discussion have indicated that the steel is self-hardening, that is, will harden on cooling in the air.

The following heat treatment was given to specimens broken off from sample No. 3 to determine whether the structure of the cast metal could be refined and improved:

SAMPLE NO.	ANNEALED AT	TIME OF ANNEALING TEMPERATURE.
3-A	900° C.	5 hours
3-B	900 "	2 "
3-C	900 "	½ "
3-F	1000 "	4½ "
3-G	1000 "	1½ "

Micrographs showing the structure of the cutter after the treatment indicated in the foregoing are shown in Figs. 9 to 13 inclusive.

Cutting tests on hack saw blade, sample No. 5, were made in comparison with similar tests on a tungsten "Star" hack saw blade of similar size, tooth construction, etc. Thirty-five cuts were taken with each of the two blades; in each of the cuts the two blades operated under the same speed and pressure. The tests were made on a Milford power hack saw machine with a 5¾-in. stroke; cuts were made through 1¼ in. round soft machine steel. In each cut, the colbaltcrom blade proved itself superior to the tungsten blade, the number of strokes necessary to cut through the steel varying from 237 to 270 with the cobaltcrom blade, and from 326 to 563 with the tungsten blade. A pressure of 20½ lb. was used in all except a few of the cuts made.

The effect of heat treatment on the scleroscope hardness and microstructure of the forged cobaltcrom bar, in comparison with the effect produced under similar and parallel conditions, on two compositions of tungsten high speed steel (Rex AA and

Capt. Baxter.

Mushet), was then studied. The three samples studied showed the following chemical analyses:

	SAMPLE NO. 6.	REX AA.	MUSHET.
Carbon	1.64	0.77	1.91 per cent
Manganese	0.29	0.25	1.49 "
Nickel	0.50	....	Not Detected
Silicon	0.206	0.474	0.919 per cent
Chromium	13.61	3.47	1.33 "
Tungsten	Not Detected	17.8	7.43 "
Cobalt	2.85	....	....
Vanadium	0.05	0.74	0.11 "
Molybdenum	0.60	0.065	0.23 "

The purpose of the tests was to obtain relative indications of the "red hardness" of the cobaltcrom and tungsten types of high speed steel and to determine the best hardening temperature for the former. In these experiments the steels were hardened from various temperatures and the scleroscope hardness measured at room temperatures following tempering at temperatures below the critical point on heating. The cobaltcrom samples were given a uniform quenching treatment, which consisted of "air hardening," that is, cooling the sample in the air from the quenching temperature for about one minute, in which time the sample had cooled to a black heat, and then dipping it in oil. The Rex AA steel was oil-quenched and the Mushet steel water-quenched. The results obtained indicated that the initial hardness of the cobaltcrom sample, that is, as tempered at ordinary temperature (25° C.), increases with the hardening temperature from 930° to 990° C., then remains fairly constant up to 1040° C., after which it drops abruptly with further temperature increments. The results furthermore indicated that cobaltcrom possesses the property of resisting loss of hardness by tempering, namely, "red hardness," and that that property increases with the hardening temperature, which is a well-known phenomenon exhibited by high speed steels. The parallel tests run on the Rex AA steel indicated that the highest quenching temperature, 1290° C., probably represents the best hardening temperature, while for the cobaltcrom steel a temperature between 1030° and 1040° C. is probably the best, since on heating higher that steel is considerably softened due to the formation of some

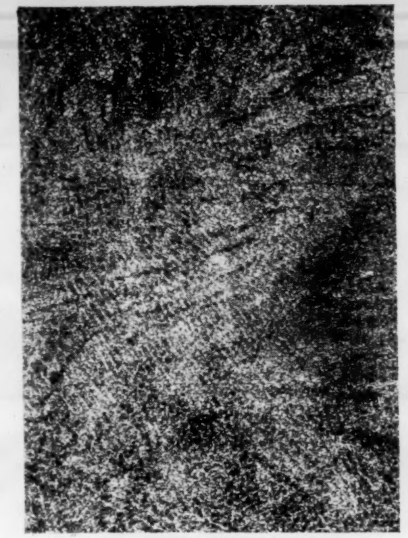

FIG. 9.—Surface Metal (× 100).

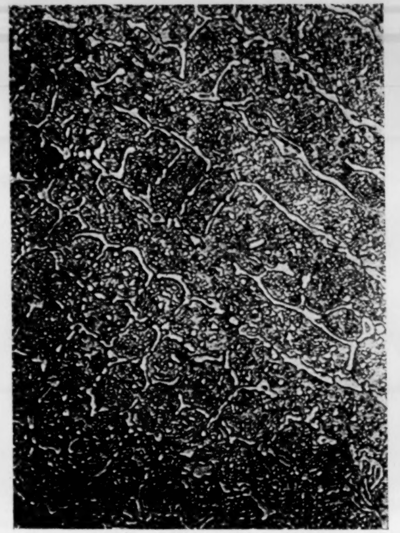

FIG. 10.—Surface Metal (× 500).

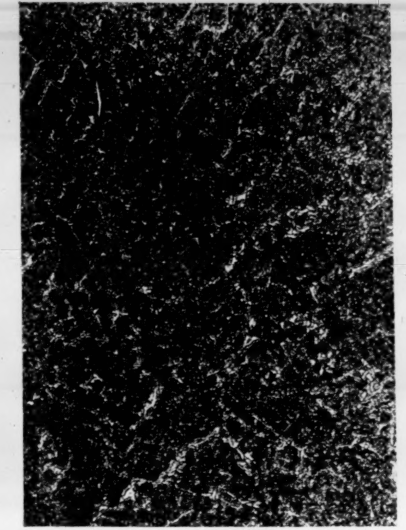

FIG. 11.—Central Portion of Cross-Section (× 100).

FIG. 9.—The metal consists of a network of the hard brittle carbide embedded in a granular matrix. The matrix itself contains numerous small globules of carbide.

FIG. 10.—The metal consists of a network of the hard brittle carbide embedded in a granular matrix. The matrix itself contains numerous small globules of carbide.

FIG. 11.—The metal consists of a network of the hard brittle eutectic. The matrix itself contains numerous small globules of carbide.

CAST MILLING CUTTER, COBALTCROM STEEL. ETCHING, 2 PER CENT ALCOHOLIC NITRIC ACID.

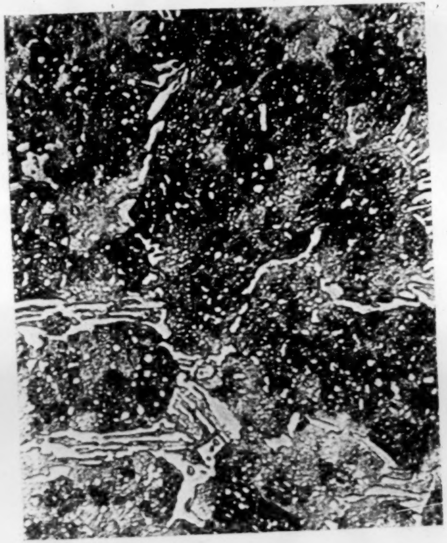

FIG. 12.—Annealed ½ Hour at 1100° C.

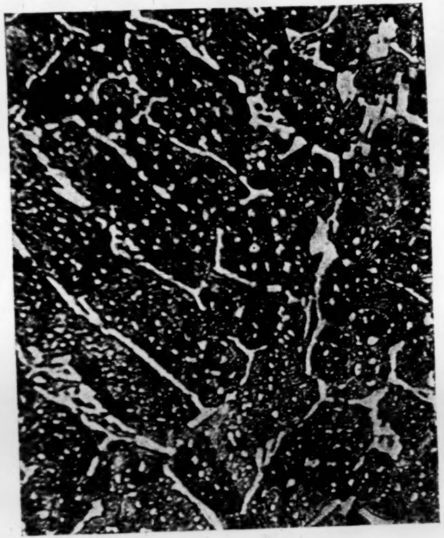

FIG. 13.—Annealed 5 Hours at 1100° C

FIG. 12.—The carbide network is unchanged by annealing.
FIG. 13.—The carbide network is unchanged by annealing. The globules within the matrix of the crystals have increased somewhat more than in Fig. 12.

CAST MILLING CUTTER, COBALTCROM STEEL. ETCHING, 2 PER CENT ALCOHOLIC NITRIC ACID (× 500).

Capt. Baxter. austenite. The curves obtained furthermore indicated that cobaltcrom commences to lose in hardness at a temperature about 100° C. lower than does the Rex AA steel. It was furthermore found that the hardness lost by cobaltcrom on over-heating might be partially regained by reheating to the tempering temperature which gives maximum hardness, and that the effects of over-heating might be completely nullified by immersing the specimen in liquid air for 30 minutes, as follows:

AIR-HARDENED FROM:	SCLERESCOPE HARDNESS AS HARDENED:	AFTER LIQUID AIR TREATMENT:
1105° C.	60	82
1150° C.	47	76

Cutting tests were made on two cobaltcrom tools (samples Nos. 7 and 7*a*) and on a tool of Rex AA tungsten high speed steel of the same size. The three tools were rough ground to the same shape, heat-treated, and then ground to the same shape on a universal grinder. The angle of the cutting face of the tool with its axis was 39 deg.; its clearance was 9½ deg.; its back slope was 16 deg. and side slope 18 deg.; the nose was rounded on a $\frac{1}{16}$-in. radius. The Rex AA tool used for comparison was of the composition: carbon 1.03 per cent, chromium 3.31 per cent, tungsten 17.6 per cent, vanadium 0.28 per cent. The composition of the material cut was: carbon 0.66 per cent, manganese 0.50 per cent, silicon 0.46 per cent. The tests were made in a Niles-Bement-Pond Le Blond 34-in. motor-driven lathe. The tools were run under constant conditions of depth of cut, feed and time. The results of the tests indicated that the tungsten high speed steel was superior for the purpose in question to the cobaltcrom steel.

The third series of tests was conducted at the Washington Navy Yard, the immediate object of the tests being to correlate and compare the mechanical performance of cobaltcrom tools and tungsten high speed steel tools.

Four exactly similar cutters, two made from cobaltcrom and two from tungsten high speed tool steel, were used in the tests; the cobaltcrom cutters will be referred to as C and C_1; the tungsten cutters will be designated T and T_1.

Capt. Baxter. The tungsten high speed steel cutters were made from Navy bar stock, $3\frac{1}{2}$ in. in diameter. The material was heated to about 1400° C. and forged for the purpose of improving the grain of the metal with the idea of obtaining the maximum cutting properties which might be expected from the best grain refinement. Cutter *T* was heated to 1230° to 1260° C., and cooled in air; cutter T_1 was heated to 1230° to 1260° C., and quenched in a mixture of two parts cylinder and 5 parts paraffin oil and then drawn in sperm oil at 288° C.

The cobaltcrom cutters were treated as follows: Cutter *C* was heated to 1030° C., cooled in air for one minute and then quenched in oil; cutter C_1 was annealed by heating to 1000° C. and cooling slowly in the furnace, then hardened by heating slowly to 1000° C., remaining in the furnace until the temperature dropped to 970° C., then cooled in air and quenched in oil when the red color disappeared in subdued daylight.

The chemical characteristics of the cutters tested were as follows:

	COBALTCROM.	TUNGSTEN TOOL.
Carbon	1.50	0.71
Manganese	0.20	0.38
Phosphorus	....	0.012
Sulfur	....	0.017
Silicon	0.75	0.23
Chromium	13 to 14	4.23
Vanadium	....	....
Tungsten	....	17.24
Cobalt	3.50	....
Molybdenum	0.75	....

After being heat-treated, all four cutters were ground to the same size (4 in. in diameter, 20 teeth, 0.234 in. in width) on the same arbor.

The tool hardness of the four cutters was as follows:

	BRINELL HARDNESS NUMBER.	SCLEROSCOPE HARDNESS UNIVERSAL HAMMER.	RATIO OF BRINELL VALUE TO SCLEROSCOPE.
Cobaltcrom *C*	689	89.6	7.69
" " C_1	871	87.6	7.67
Tungsten *T*	664	86.6	7.67
" T_1	658	86.2	7.64

Capt. Baxter. Performance tests were made using a No. 2 Brown & Sharpe belt-driven milling machine. All of the runs made employed two cutters on the arbor, each pair being mounted on the arbor so as to take cuts about 1½ in. apart from a piece of nickel steel about 20 in. in length, which was selected for the purpose on account of its thorough refinement by forging and heat treatment; there is reason to believe that the nickel steel in question was uniform throughout. After making eight cuts in a given position, the cutters were adjusted to a new position on the test block, that is, the grooves were never allowed to exceed 0.8 in. in depth. The cutting speed was varied from 114 ft. per minute, peripheral, to a maximum of 330 ft. per minute; the feed was varied from 8 in. per minute to a maximum of 21 in. per minute. The results of the tests, summarized, which cover from 50 to 70 runs, showed that both the cobaltcrom and the tungsten steel cutters made an unusually good record, compared with current experience with the best grades of high speed tool steel. While the tungsten cutters were slightly superior to the cobaltcrom cutters, the performance tests made indicated that under slightly different conditions their mechanical performance would probably have been about equal. The results seemed to indicate that when production is of secondary importance in comparison with precision, cobaltcrom tools compare favorably with tungsten high speed tools; but where the main purpose is to secure production, tungsten high speed tools are preferable.

Conclusion.—The data and information contained in this discussion are submitted as a matter of possible interest and technical use only, without any inference relative to or bearing upon the Navy's policy as a user of high speed tool steel; the discussion is offered only to further the development of modern high speed tool steels.

Mr. Kenney. MR. L. H. KENNEY (*presented in written form*).—I have read Mr. Mathews' paper with much interest and consider it a valuable contribution to the Proceedings of the Society. Mr. Mathews refers to physical tests to determine the cutting characteristics of various compositions of high speed steels. A test was developed by the Philadelphia Navy Yard in order to provide information on which to base a recommendation for award of contract. Many of the tool steel contracts are in force

Mr. Kenney.

for a year in order that steel in the sizes and quantities required can be purchased at any time during the year without inviting further bids. The specifications require the bidders to submit a sample bar long enough to make five lathe tools. The bars are cut into five pieces, numbers are assigned to each piece at random so that the tools made from any one sample bar are seldom consecutive; from there on the tools are treated in consecutive order. By treating and testing the tools in sequence, it is considered that the variations in furnace temperature and homogeneity of the steel forging on which the tools are tested would be pretty well balanced.

First they are rough-ground to a No. 30 Sellers' form for lathe tools without forging of the bar. The tools are then given the heat treatment, either the standard selected for this purpose, or in accordance with the information furnished by the bidder. After heat treatment the tools are ground and are ready for the cutting test. A nickel-steel forging is used for the test and a definite depth of cut, feed, and cutting speed are selected and remain constant throughout the test. The length of time the tools cut before they break down is recorded. A graphic wattmeter is connected across the leads to the motor driving the lathe, and a record obtained of the watts required to operate the lathe when cutting and when not cutting.

After the physical test is completed, a computation is made to determine the relative merits of the various samples. The product of the watts as determined by the graphic wattmeter and the time the tool cuts gives the "work done." The probable value of the "work done" is determined by the method of least squares. Occasionally an excellent run is rejected as well as a poor run. The probable "work done" is compared with the price of the material and forms the basis for selection.

The method described requires considerable time, and it would be very desirable if some less expensive and less time-consuming test could be devised which would give satisfactory results. Mr. Mathews in his paper refers to several other tests, and it would be very desirable if others interested in the subject of determining the relative merits of tool steels could devise a satisfactory and relatively inexpensive test.

Mr. Rettew. MR. E. W. RETTEW (*presented in written form*).—Mr. Mathews deserves the thanks of the Society for his able presentation of a subject which is of such great importance to the steel manufacturer and consumer. There are, at the present time, a considerable number of high speed steels on the market for which phenomenal performance is claimed because of the presence therein of one or more of the elements uranium, cobalt, molybdenum; it is refreshing indeed to have a statement from one of recognized authority that no generally accepted improvement has been made in high speed steels since the introduction of vanadium some fourteen or fifteen years ago.

Knowing that the subject of high speed steel was to be presented at this meeting, the writer has made during the past three months a careful study of a considerable number of high speed steel analyses, representative of present American practice, from which he has prepared the following limits and desired analysis:

	LIMITS.		DESIRED.	
Carbon..............	0.60 – 0.70		0.65	per cent
Manganese..........	0.15 – 0.40		0.30	"
Phosphorus. . not over	0.015	under	0.010	"
Sulfur....... " "	0.015	"	0.010	"
Silicon...... " "	0.30		0.20	"
Chromium..........	3.50 – 4.50		4.00	"
Tungsten...........	16.00 – 18.00		17.00	"
Vanadium..........	0.65 – 1.05		0.85	"

My own experience has been that analysis of the same brand of steel is likely many times to be widely variant in different shipments. While the writer does not wish to have his attitude construed as being opposed to research involving heretofore untried, or little used, elements as additions to high speed steel melts, he firmly believes that if steel manufacturers and users will concentrate on the standardization of raw materials, melting practice, forging and annealing processes, and methods of treatment and grinding involved in the manufacture and use of a high speed steel which shall lie within the above limits, aiming to attain the desired analysis (which, it will be noted, agrees very closely with steel No. 33 mentioned in Mr. Mathews' paper, excepting for the chromium content which is slightly higher), the improvements which very likely will be attained will be truly remarkable. **Mr. Rettew.**

There is a growing tendency on the part of large consumers to purchase their tool steel according to some specified analysis and this tendency is no doubt being evidenced with regard to high speed steel. While it is agreed this is a very difficult and perhaps undesirable attitude to take with regard to high speed steel, because so much of the success of high speed steel depends on excellence of melting, it is hoped that the subcommittee on tool steel will do everything in its power to standardize this very important product.

Mr. Hoffman. MR. N. B. HOFFMAN (*presented in written form*).—Commenting on Mr. Mathews' very able paper, I would say I can agree with his version on the use of uranium in high speed steel, at least when 0.20 or 0.30 per cent of uranium is used to displace 10 to 12 per cent of tungsten and obtain the same efficiency from the steel. I have made numerous tests with uranium and from the results obtained fail to see that it has any virtue in a high speed steel.

I do not, however, feel the same in reference to cobalt. Having made numerous tests on cobalt high speed steel during the past five years, and on competitive tests with various compositions, with and without cobalt, I feel satisfied that it has a distinct advantage over non-cobalt steels when in the proper proportions, although I do not think it could be used as a substitute for any other elements regularly present. I have tried out high speed steel with cobalt varying from 0.5 to 6 per cent, and have found the best results were obtained with between 2 and 2.5 per cent; the higher and lower percentages of cobalt did not seem to improve the steel in the same degree.

Tools made from cobalt steel seem to produce the best results when heated to 2300° F., and cooled by an air blast, the temper being drawn after hardening to 850° F.; while to get the best results from modern high speed steels, practically all manufacturers advise heating the tool to 2200° F., immersing in oil and then drawing the temper to the proper degree of hardness required for the purpose (from 400° to 850° F.).

Mr. Hoffman. The following is an approximate analysis of the cobalt steel in question:

Carbon	0.70	per cent
Manganese	0.25	"
Phosphorus	0.014	"
Sulfur	0.016	"
Silicon	0.35	"
Tungsten	17.50	"
Chromium	3.75	"
Vanadium	1.30	"
Cobalt	2.50	"

Competitive tests have been made under the same conditions, with steels containing the above approximate analysis, with and without cobalt, and the cobalt has proved superior in every case.

I have also tried nickel in place of cobalt; a tool with the following analysis was used:

Carbon	0.70	per cent
Manganese	0.28	"
Phosphorus	0.016	"
Sulfur	0.018	"
Silicon	0.38	"
Tungsten	18.18	"
Chromium	3.91	"
Vanadium	1.33	"
Nickel	1.73	"

Steels of this type did good work in ordinary shop practice, but when subjected to fast heavy work they were no better than standard high speed steel.

The cobalt steel does its best work when used as lathe, planer and boring tools, and when run at high speeds and on heavy cuts. I have no knowledge of the competitive test Mr. Mathews mentions in his paper, but I have many of my own and will review several of them.

One test was run on locomotive driving wheels, 64 in. in diameter. The size of tool was 3 by $1\frac{1}{2}$ in., the speed $18\frac{1}{2}$ ft. per minute, the feed $\frac{3}{8}$ in. and the cut $\frac{3}{8}$ to $\frac{1}{2}$ in. Eleven tires were finished per grind of tool; the shop record was five tires per grind.

Mr. Hoffman.

A second test was on shell turning. The tests were run on twelve Le Blond lathes, operating continuously for from three to four weeks, working on forged 3-in. Russian and United States shells. The size of the tool was $1\frac{1}{4}$ by $\frac{3}{4}$ in., the speed 72 ft. per minute, the feed $\frac{1}{16}$ in., and the depth of cut $\frac{1}{8}$ in. The shells were 3 in. in diameter and $11\frac{1}{2}$ in. long. The average results were 90 United States shells and 110 Russian shells per grind of tool.

I thoroughly agree with Mr. Mathews that steel-making is the first requisite necessary in determining the quality of high speed steel, the manufacture of which, with its complex alloy composition, is a task of no mean proportion, and calls for an experienced personnel in every step.

Mr. Scott.

MR. HOWARD SCOTT (*by letter*).—In his admirable résumé of the present status of our knowledge of high speed steels, the author has discussed two lines of research in which the writer is particularly interested. The first is the effect of quenching and tempering temperature on the physical properties of these steels as related to the accompanying structural changes, and the second is the need of a cheaper and quicker method of determining "red hardness" than the usual cutting tests.

In regard to the first problem, the writer wishes to state that his observations on several physical properties of a typical chrome-tungsten high speed steel confirm those of Mr. Mathews, with the possible exception of his statement that he found no secondary hardening on tempering. Thus the scleroscope hardness of a 0.77-per-cent carbon, 18-per-cent tungsten and 3.5-per-cent chrome steel quenched from 1300° C. (2372° F.), at which temperature superficial fusion occurs, averages 75 at tempering temperatures below 600° C. (1112° F.); but between 600° and 700° C. (1112° and 1292° F.) it varies from 80 to 85. The coercive force also averages 51 up to 500° C. (932° F.) but at 600° C. (1112° F.) it jumps to 55. This work, which it is expected will soon be complete, appears to offer a simple explanation of the phenomenon of secondary hardening.

As to the second problem of a simple method of measuring "red hardness," the writer cannot agree with the opinion of Mr. Mathews that the method of measuring "red hardness" by noting the tempering temperature at which the maximum loss

Mr. Scott. of hardness occurs (assuming that this measures "red hardness," as he appears to and the writer believes it does) is too expensive and laborious as a substitute for cutting tests. This opinion is based on reference to records of the Bureau of Standards showing that nine samples were tempered at five different temperatures, and the scleroscope hardness taken after each treatment in one day occupying only a part of the time of two observers. The desirability of a still quicker and simpler test is, however, apparent, and the writer has undertaken to apply thermal analysis to this problem, as the work of Carpenter[1] suggests that the temperature of the heat effect accompanying tempering is a measure of "red hardness." To this end tests have been inaugurated on a series of tool and high speed steels having a considerable range of "red hardness" in an effort to connect this property, as measured by cutting tests, with the same property as measured by the hardness-tempering method and by thermal analysis.

Mr. Mathews. MR. JOHN A. MATHEWS (*Author's closure by letter*).—The generous discussion by men so well qualified to express opinions upon high speed steel convinces one of the wisdom of the Committee on Papers in selecting this subject for special consideration. That there should have been some differences of opinion was to have been expected, but that there should have been substantial agreement upon the principal points involved, is more surprising. The author takes satisfaction in the fact that his efforts to present the subject fairly and impartially have met with the approval of both makers and users of high speed steel.

In regard to the communciation from Captain Baxter, Bureau of Construction and Repair, U. S. N., it might be said, in so far as tungstenless high speed steels are concerned, that these have been for the most part tried and found wanting in the United States during the earlier years of the high speed steel industry. In this category may be included molybdenum, chrome-molybdenum, chrome-molybdenum-cobalt, and high chrome substitutes for tungsten high speed steel both with or without vanadium. The writer has personally had experience with all of these combinations from 1902 down to the beginning

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[1] Carpenter, *Journal*, Iron and Steel Inst., Vol. 67, pp. 433–473 (1905). Scott, *Bulletin No. 146*, Am. Inst. Min. Eng., Feb., 1919, p. 157.

Mr. Mathews. of the European war, and probably many other manufacturers of tool steel have had the same experience. During the war, when the tungsten shortage confronted us, it was but natural that as an economic measure the use of these materials should have been revived, and rightly so. From the standpoint of dependability, and relative efficiency, they are not likely to become serious rivals of tungsten high speed steel. The American users, however, should not get the impression that there is anything new or revolutionary in regard to the tungstenless products, for they are, in fact, ancient history to those familiar with the art of tool steel manufacture.

Captain Baxter's report confirms the opinion expressed in regard to these tungstenless products, and a word of caution might not be out of place in regard to the comparison of hack saws made of air-hardening steel and those made of ordinary tool steel carrying a very small amount of tungsten. The comparison is hardly a fair one.

The principal points the author tried to emphasize were, first, the futility of over-emphasis upon the part of many users of high speed steel of one constituent (usually tungsten) in a highly complex chemical product of at least ten variables. Certainly as many more physical variables enter into the final quality of the product. Second, the need of chemical and physical methods for determining (*a*) the best heat treatment for a given steel, and (*b*) the relative merits of different steels without resorting to the very difficult and expensive cutting tests.

It is hoped that the paper and discussion may lead to investigations being inaugurated which will solve one or both of these problems.

DEEP ETCHING OF RAILS AND FORGINGS.

BY F. M. WARING AND K. E. HOFAMMANN.

SUMMARY.

This paper presents the results of some deep etchings with hot acid on both new and old rails and forgings. Under this process defects in the steel, having the appearance of cracks, have been developed to visibility.

These defects could not be found with light etching and apparently are caused by actual cracks in the steel extending through solid crystals as well as following the crystallin boundaries.

The authors are not prepared to offer any theory for the origin of the defects found, but submit these results of their investigation in the hope of promoting discussion and securing the cooperation of both steel makers and users in future work along these lines.

DEEP ETCHING OF RAILS AND FORGINGS.

By F. M. Waring and K. E. Hofammann.

Deep Etching of Rails.

The origin and development of the defects known as internal transverse fissures which are the cause of a certain type of rail failure have been a matter of much discussion, and different authorities have offered various reasons for the existence of these defects, such as: impurities in the steel, gagging, internal stresses resulting from non-uniformity of cooling of the rails, internal stresses set up in the rail while in service under the moving wheel loads, etc.

In some of the many investigations that have been made upon rails which failed due to transverse fissures, etchings of transverse specimens have shown the existence of small cracks located principally near the center of the head, but none of the reports containing reference to such cracks attempted any explanation of their presence, or carried the investigation far enough to show that similar cracks could be found on etchings of longitudinal sections through the head of the rail. It was in attempting to investigate the nature of these small cracks appearing in transverse sections of the rails that we were led to extend our investigation to include longitudinal sections about $\frac{1}{2}$ in. thick and 18 in. long taken from the center of the rail head. Light etchings of such sections did not develop any defects and the etching process was then continued with concentrated acid with results that were to us very surprising and wholly unexpected.

Fig. 1 shows the appearance of such a slab from a rail which had developed twelve transverse fissures when broken under the drop test. This specimen was etched for two hours in a hot solution of 9 parts hydrochloric acid, 3 parts sulfuric acid and 1 part water. The action of the acid has opened up both transverse and longitudinal fissures whose existence could not be detected under the light etching to which this slab had previously been subjected. This specimen was from an old rail which had been in the track for about five years, and the entire heat, consisting of 61 rails, had been removed on account

FIG. 1.—Photograph T-10396, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen from Old Rail that showed 12 Transverse Fissures.

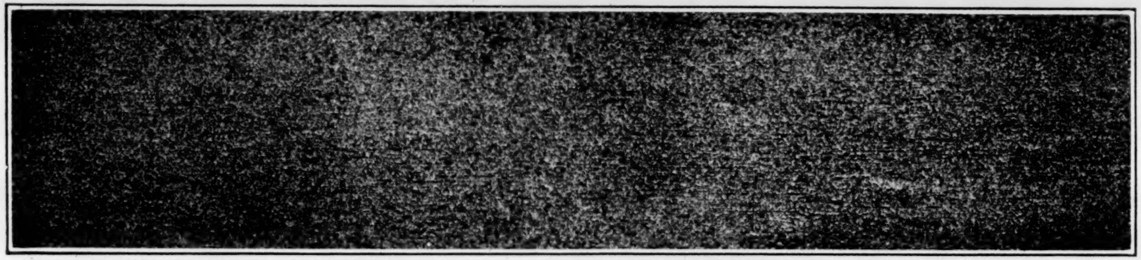

FIG. 2.—Photograph T-10399, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen from Old Rail that had No Transverse Fissures.

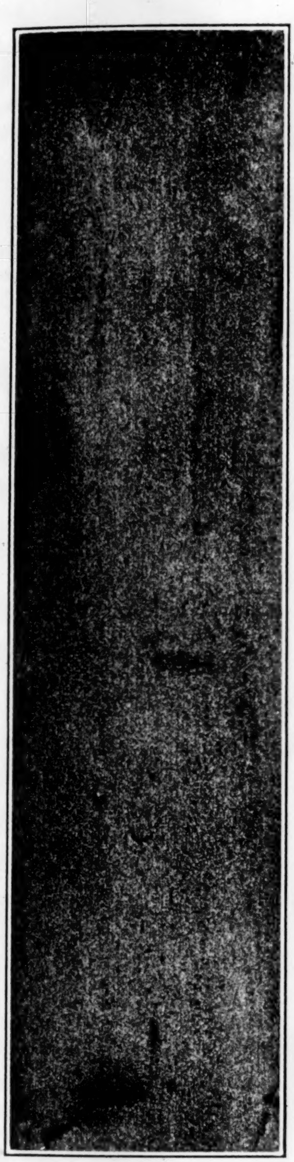

FIG. 3.—Photograph T-10401, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen from New 125-lb. Rail.

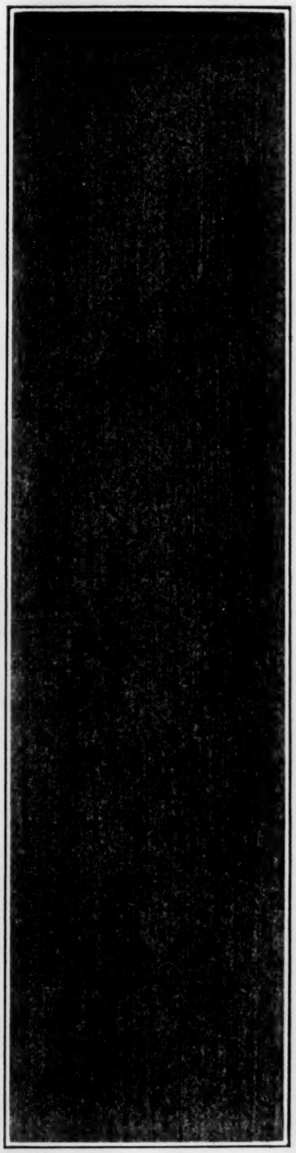

FIG. 4.—Photograph T-11056, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen from New 130-lb. Rail.

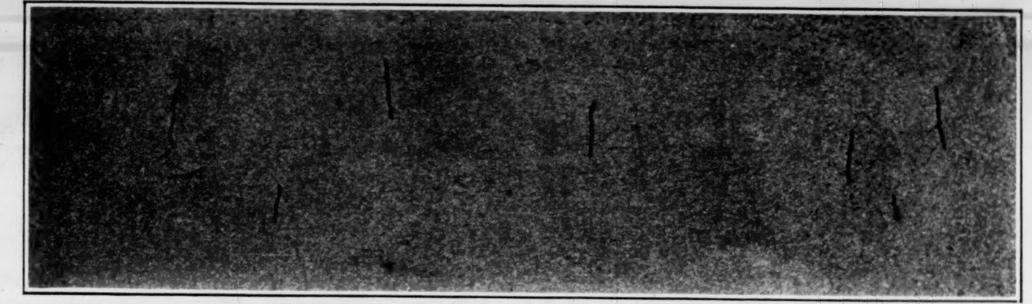

FIG. 5.—Photograph T-10790, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen is a Tangential Section from a New Tire.

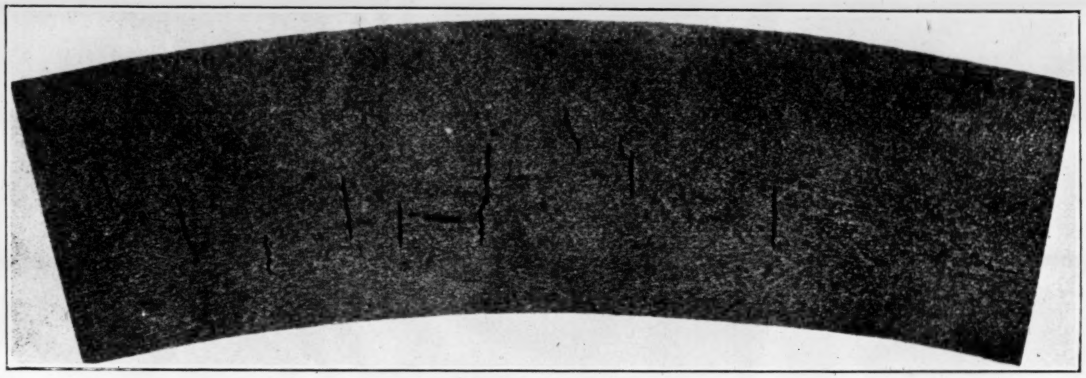

FIG. 6.—Photograph T-10791, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen is a Radial-Longitudinal Section from a New Tire.

of a number of failures from transverse fissures. Similar treatment of slabs from other rails in the same heat which had shown transverse fissures also gave the same indications to a greater or less degree, there being apparently some improvement in the appearance of the steel and a smaller number of defects opened up under the action of the acid for those rails which showed only a few transverse fissures when broken under the drop test.

Fig. 2 shows the appearance of a deep etched slab from one of the rails which did not contain any transverse fissures. This section is entirely free from any of the cavities which were opened up in the specimen mentioned above.

The existence of these defects in rails which had developed transverse fissures and the failure to find them in rails from the same heat of steel which had been subjected to the same traffic conditions suggested that the investigation should be extended to include new rails. Fig. 3 shows the deep etching of a slab from a new 125-lb. rail, and Fig. 4 from a new 130-lb. rail, which had never been in the track. Both of these new rails contain a number of defects similar to those found in the old rails.

DEEP ETCHING OF TIRES AND WHEELS.

The results of deep etchings on rails led to the conclusion that some of the trouble that is experienced with the breaking of steel tires might be due to the presence of similar defects. A new locomotive trailer wheel tire, which had made only about 25 miles before breaking, was cut into tangential and radial longitudinal slabs through the center of the section and these were deep etched with the hot acid solution with results as shown in Figs. 5 and 6.

A new rolled steel wheel which had cracked before being placed in service was cut up so as to obtain a tangential longitudinal slab from the center of the rim and when this was subjected to the hot deep etching solution, internal defects were found as shown in Fig 7.

SUMMARY.

This investigation by means of deep etching with hot acid has developed the existence of interior defects in rail heads, which defects appear to be more frequent in rails that have developed a number of transverse fissures than in others which had only a few or no such fissures. They have also been found to exist in new rails which have not been in the track. It appears that these concealed defects cannot be detected by the usual methods of investigation and tests, or even by the usual method of etching.

Similar interior defects have been developed in a new tire and in a new rolled steel wheel.

Microscopical and chemical examination of the sections containing these defects have not, so far, developed the existence of any inclusions between the faces of the cracks and there is no apparent difference in the microstructure of the steel in these locations which would account for the action of the acid. After one of these cracks has been lightly developed and the surface polished and examined under the microscope the defect has been found to extend through the crystals, as well as following the boundary lines.

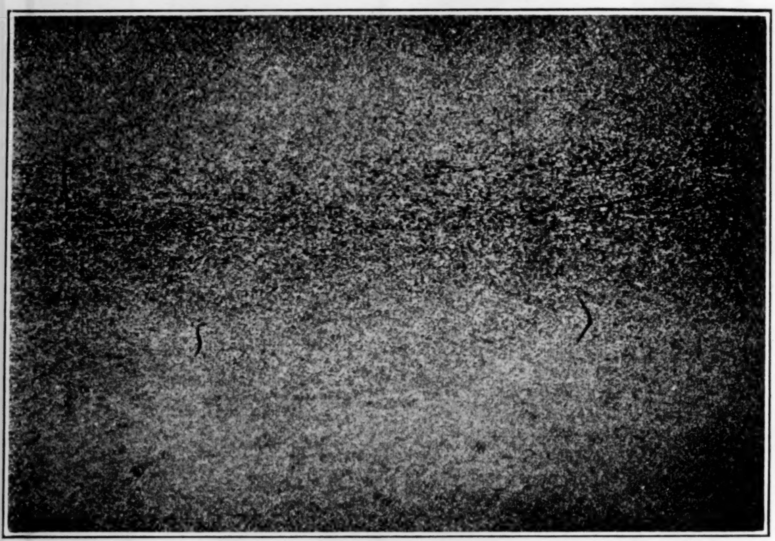

FIG. 7.—Photograph T-10792, Reduction one-half. Etched with 9 HCl, 3 H_2SO_4 and 1 H_2O at Temperature of 200° F. Specimen is a Tangential-Longitudinal Section from a New Rolled Steel Wheel.

The manner in which the acid attacks these defects and rounds off the edges, leads us to speak of them as cracks, but so far the investigation has not developed the cause. We are inclined to believe that the cause must be sought in the mill during some stage in the process of fabrication of the material.

DISCUSSION.

Mr. J. A. Capp (*presented in written form*).—The results reported by Messrs. Waring and Hofammann are very interesting. Not the least interesting fact is that the fissures which open up during the prolonged pickling, or etching as the authors prefer to call it, appear to develop in sound metal. None of the ordinary means of examination employed have shown any indication of a crack or fissure existing at those places where cracks develop after long immersion in strong acid. The cracks do not seem to select their path with respect to structural constituents so far as the authors have observed. For these reasons, it has been difficult for one to arrive at a satisfactory explanation of the development of the cracks. **Mr. Capp.**

It is common knowledge that when hardened steel parts, such as springs, are pickled in acid they will frequently break up. Some years ago there were several papers on this subject published in the Proceedings of the American Electrochemical Society, which purported to prove that the breaking of the hardened steel springs was due to the absorption by the steel of the hydrogen liberated at the surface of the steel by chemical action of the pickle bath. The explanation given was that atomic hydrogen will penetrate freely into the steel; in fact, that it will pass through such thin sections as springs are usually made of. Wherever the atomic hydrogen finds sufficient room in the steel to unite with other atomic hydrogen to form the molecule of hydrogen or H_2, enormous pressure is set up. When the steel is already in a highly strained state it is claimed that the additional strains set up by the internal pressure developed by the formation of the hydrogen molecules is sufficient to rupture the steel. As further evidence it is pointed out that annealed steel, which is free from internal strain, is not ruptured by the internal gas pressure. Work which has been done in the Research Laboratory of the General Electric Co. has appeared fully to confirm the claims made for the validity of this explanation of the cause of rupture of hard steel by pickling.

Mr. Capp. The articles which have been examined by Messrs. Waring and Hofammann are of fairly hard steel and the methods of manufacture of them are such that an internally strained state may be expected. The acid used by the authors is strong and it is very active at the temperature employed. May it not be the case, then, that the fissures which develop are the result of the gas pressure added to the internal strain? Obviously, the formation of molecular hydrogen does not require large spaces. In fact, the spaces in which the gas atoms may collect to form H_2 may easily be ultra-microscopic; yet these same spaces might conceivably be the points of weakness which would determine where failure would occur in any ordinary test or as the result of repetitive loading.

Through the courtesy of Mr. A. W. Gibbs, I had the opportunity to read the report upon which this paper is based. This possible explanation of the development of the cracks occurred to me and I suggested that it would be interesting to take two adjacent specimens, one of them to be pickled just as taken and the other to be pickled after annealing. If the explanation is correct, the hard specimen should crack while the annealed piece should show no cracks.

Mr. Waring. MR. F. M. WARING.—In reply to Mr. Capp, I would state that so far we have been able to carry out this annealing test only on one piece of rolled steel tire. Two slabs were cut from this tire, one slab being polished and etched in the original condition, and the other subjected to annealing at 900° C. and then etched with the hot acid. The annealed slab developed about as many cracks as the slab etched in its original condition, but it seems to me that the effect of annealing should be investigated further.

We have been very much encouraged by the interest that has been taken in this subject by a number of other investigators, and we hope, from the work that is now being done, that within a short time we will be able to obtain considerably more information as to the nature and cause of these cracks and what should be done to eliminate them.

Mr. Howard. MR. JAMES E. HOWARD (*presented in written form*).—Generous thanks are due Messrs. Waring and Hofammann for the presentation of their paper; a brief statement of some facts observed by them, which directs attention to matters of deep interest. A shattered state of the metal in the interior of certain steel rails and steel tires has been shown, which they revealed by the method of deep etching, or as it is more commonly called by means of pickling in hot acids. **Mr. Howard.**

This paper revives and extends the scope of a method of examination which a term of years ago was much in use. The authors, however, have shown in their observations that the method of pickling may reveal features pertaining to the interior state of the steel, specifically on longitudinal sections of rails, which, under the action of less energetic etching solutions or solvents, have not attracted attention.

The pickling of castings, forgings, rolled plates, and drawn rods is a commercial process employed to meet manufacturing and mechanical conditions. As a laboratory method it has also been employed, but without touching upon the apparently vital features in the structure of the steel which the authors have so well illustrated. Thus a somewhat neglected method of examination, of considerable antiquity, has been turned to a new use, and credit attaches to those who have by this simple method shown important truths and have given an impetus to further inquiry along lines so clearly pointed out.

The authors state that no microscopic or chemical cause has been discovered which would account for the presence of the cracks which the pickling reveals; furthermore, that the courses of the cracks, when lightly developed, have been found to pass through the crystals as well as following their boundary lines. The authors conclude that the cause of these manifestations must be sought in the processes of fabrication of the material, which it would seem must be the case since the rails and wheels upon which their observations were made were new and had not been in service.

The pickling done by the authors was with a solution of hydrochloric acid, to which some sulfuric acid had been added, and diluted with a small quantity of water. Other solvents may be used with success. Commercial muriatic acid used alone reveals these cracks, dilute sulfuric acid also serving the same purpose. Less energetic solvents may be employed and not unfrequently to advantage. There is danger of removing so

Mr. Howard. much metal by an energetic solvent that important evidence may be lost before the action of the solvent is arrested. If prolonged, ultimately, the steel would all go into solution.

Fundamentally it is desired to establish whether the cracks which make their appearance after pickling existed as cracks prior to pickling. Evidence at hand leads to the conclusion that the cracks were pre-existent. They have not always been found by microscopic examination in such numbers as the acids reveal, and in some cases a careful microscopic inspection has failed to locate any of them, especially when picric acid was used in the etching solution.

In this connection it would be of interest to ascertain the distances which separate the faces of these cracks in their primitive condition. It is probable that no metallurgical necessity exists for the opposite faces of a crack being separated a measurable distance; meaning by this a space approaching even a fifty-thousandth of an inch. There is considerable uncertainty attaching to an attempt to accurately measure the distance from face to face of a crack, of course viewing the crack on edge when undertaking to do so. So nearly or quite in contact are the faces of certain cracks that a mild solvent is required to reveal their presence on a polished surface. But cracks visible to the eye on machined surfaces have been lost to view when the steel was polished for microscopic examination, and restored to view by the use of a mild solvent.

Investigations are in progress having for their object the determination of the period, with relation to temperature, when the shattering takes place, not confining the observations to one grade of steel but including those of different degrees of chemical hardness. Two basic questions are presented in the consideration of this subject, namely, the zone of temperature in which shattering occurs, and the grade or grades of steel which are readily susceptible of such shattering.

The appearance of certain of the cracks as shown by photomicrographs is consistent with the explanation that they occur when the steel is at a fairly high temperature. A definite line of inquiry is opened by giving consideration to this hypothesis.

The orientation of the cracks indicates the relief of forces which acted in different planes, with a preponderance, however, in

Mr. Howard.

a lateral or crosswise direction. Something might be said about the usual laminated striations parallel to the length of rolled shapes and their influence on these results.

If they represent shrinkage cracks their development appears to call for the presence of simultaneous compressive strains in other portions of the cross-section of the rail or tire. Probably a difference in strength and rigidity in different parts of the cross-section obtains at the time of their formation, due to differences in temperature of the steel. This line of thought leads to the inference that the shattering occurs during the prevalence of conditions found in the latter stages of the rolling or forging operations, or soon after their completion. During cooling internal strains are generally set up in cast, rolled and forged shapes. At an early stage, when the interior metal is hotter than the peripheral, the latter is put temporarily into a state of tension, which changes to a state of compression when the interior has cooled. This reversal of internal strains accounts for the introduction finally of a force of the kind required to rupture the interior metal.

It is necessary to explain or offer a conjectural reason why the peripheral metal does not rupture or escapes the tendency to do so when in a state of tension, although the interior metal is expected to do so under the same kind of strain. The peripheral metal when under tension is not restrained from radial contraction, therefore can display the phenomenon of permanent set or permanent elongation. On the other hand, the interior metal, after the cooling strains have reversed themselves, is exposed to tensile strains along each of its three axes, on account of the peripheral metal then being in compression. The phenomenon of permanent set or elongation can hardly take place when the metal is strained in three directions. Strained in such a manner it seems possible to effect the rupture of steel without the display of elongation, other than elastic.

There is no grade of steel known which possesses a very high tensile strength at rolling and forging temperatures, hence none could be expected to sustain without rupture a tensile stress of magnitude simultaneously received in three directions. The minimum strain necessary to cause rupture, in the absence of opportunity to display the phenomenon of elongation, must

Mr. Howard. indeed be a very limited one, and cracks formed under such circumstances need not possess a measurable width of opening between opposite faces. There seems no inconsistency in having brittleness displayed in steels at high temperatures as well as at low temperatures; but only in the quenching of steels are the necessary conditions present for accomplishing this result.

It is known by all that more care must be exercised in the heating and cooling of chemically hard steels over the softer grades. Herein lies a reason for extending the observations to the softer grades of rail steel, ascertaining the relative susceptibility of hard rails and soft rails in the display of shattered interiors. There is no grade of steel which is immune from brittleness under certain conditions which destroy ductility, but still there is a preference for the use of grades which common experience has taught are not over sensitive to slight inequalities in structure. The margin in safety is greater against exceptional stresses in those grades of steel which are least affected by mechanical action. The safer metal for general use is found in the softer grades of steel.

The authors in their opening sentence refer to the display of transverse fissures in rails. A considerable number of explanations for their occurrence have been offered from time to time. It has been difficult to trace a relation between some of the ascribed causes and their development. Explanations have been advanced which, upon collation, are found to be in pairs, with one the antithesis of the other. Many of these ascribed causes must be rejected as irrelevant.

The manifestations brought out by the authors furnish, however, unquestionable evidence of the presence of numerous cracks any one of which it would seem might be the starting point of a transverse fissure, among those properly oriented. Others might lead to split heads in which the plane of rupture is longitudinal and vertical. They also afford opportunity for the development of shearing fractures in which the upper part of the head of the rail is detached by fracture in a longitudinal and horizontal plane, or with an oblique surface. The development of each of these common types of rupture would seem to be facilitated by the presence of pre-existing cracks.

The thought occurs whether the very profusion of cracks

Mr. Howard.

in the shattered zones may not have compensating advantages in retarding, by diffusive action or by interposition, the progress of the forces which lead to the formation of transverse fissures. That is, will the rate of progress of a plane of rupture be influenced by a succession of cracks across which the plane of rupture must pass? The difference in behavior in this respect between glass and wood is obvious.

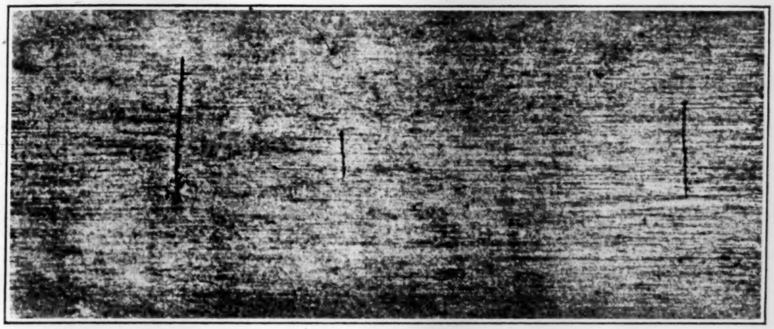

FIG. 1.—Incipient Transverse Fissures in the Head of a Rail which Failed in the Track. Top of head planed off, and pickled in hot HCl.

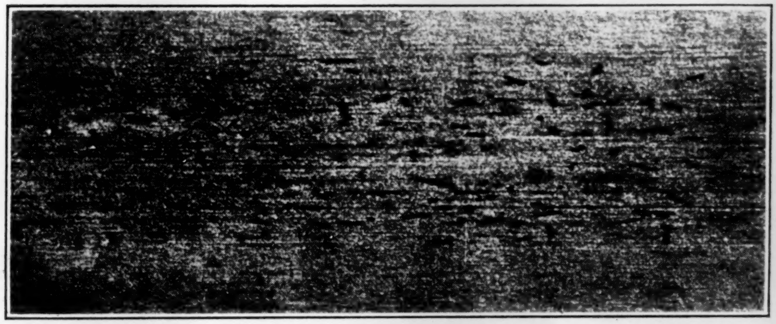

FIG. 2.—Shattered State of the Metal in the Head of a Rail which did not Fail in the Track. Removed for Examination. Top of head planed off, and pickled in hot HCl.

The writer has shown that the effect of wheel pressures on the heads of rails in service is to impart internal strains in the zone of metal next the running surface. This part of the head of

Mr. Howard. the rail acquires a state of compression which commonly amounts to about 20,000 lb. per sq. in. This state of strain explains why the fibers in the head most remote from the neutral axis are not the first to rupture in the display of transverse fissures. Internal compression as a force exists along all parts of the top of the rail and accounts for the breaking up of the head into short fragments, well advanced transverse fissures being displayed in close proximity to each other. Such fissures have been found within a distance of one inch of each other and have been located within $1\frac{1}{8}$ in. of the end of the rail.

Tests being conducted by the writer have not yet chanced to disclose shattered metal in the heads of new rails normally treated. Shattered metal was absent in some old rails from the track, which, from their partially mashed heads, appeared to be of a medium soft grade of steel; and the examination of some early rails of domestic and English manufacture did not reveal shattered metal. On the other hand one of a series of new rails, which was quenched in water from the hot saw, displayed shattered longitudinal cracks in the interior of the head when pickled.

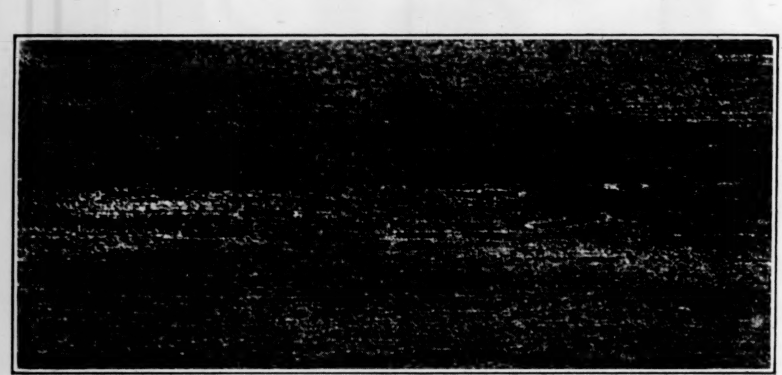

FIG. 3.—Shattered State of the Metal in the Head of a New Rail, Quenched in Water from the Temperature when Hot Sawed.

Sudden cooling sets up more intense strains of compression in the peripheral metal than normal or slow cooling. The water-quenched rail showing shattered metal, while companion pieces

Mr. Howard. cooled at a moderate rate did not, appears, in this example, to connect the shattering with the rate of cooling, and from the known relations between the rate of cooling and the acquisition of internal strains it is inferred that this rail was shattered in consequence of disrupting internal strains.

Two photographs (Figs. 1 and 2) are submitted showing the appearance of two rails after pickling, each taken on a longitudinal, horizontal section of the head. Rail A failed in the track by the development of a transverse fissure. Twenty-one incipient transverse fissures were subsequently found within a length of head of 36 in. The examination has not revealed any short shattering cracks. Rail B did not fail in the track, although it came from the same heat as other rails which did fail by transverse fissures. Upon pickling there were displayed 136 short shattering cracks within a length of head of 6 in. These were 100-lb. rails, which had been in service about six years. The rail which broke in the track was an "F" rail. The rail which did not fail was a "D" rail, referring to ingot letters. Two types of rails are here shown, according to classification with respect to shattered metal. A composite type is met in which the traits of each are present.

A third photograph (Fig. 3), rail C, shows the shattered lines which were displayed by the new rail, quenched in water. Its companion pieces cooled normally or in a breeze of air did not show shattered metal. It will be noted that the shattered lines are not present at one end of this piece of rail. The hot-sawed end was not shattered at the immediate end of the rail. It has been generally noted that the rails are free from shattered metal in a short distance from the sawed ends.

Mr. Barba. MR. W. P. BARBA (*presented in written form*).—As to deep etching and its use in determining the possible presence of fissures, either developed or potential, a good deal of work was done by the Army Ordnance Office on this matter during its manufacture of gun forgings in 1917 and 1918. Deep etching with quite strong sulfuric acid with some hydrochloric acid developed surely the locus of what later developed into fissures as well as "flakes." Flakes are many times incipient fissures, becoming fully developed upon later application of breaking force, especially when suddenly applied,—a fracture under the drop test, for instance.

Mr. Barba. Later work at the Bureau of Standards, splendidly carried on by Mr. Rawdon under Doctors Burgess and Stratton, caused us to resort to the Upton Lewis alternating-stress machine, using pieces 6 by 2 by 0.375 in., stressing them only to about 30,000 lb. per sq. in., and using as many as thirty million alternations. Mr. Rawdon applied the Coolidge tube—practically X-rays—to these pieces before, during and after rupture. The experiment was primarily started to see if known small "flakes" or incipient fissures would "run" or develop as in a detailed fracture under repeated stressing within the elastic limit. It was found that they did so develop and quite appreciably.

Now, when Mr. Waring and Mr. Hofammann showed me their work, it was at once evi ent that a similar method of research might well disclose the presence or absence of such steel defects as result in rail fissures. The deep etching can be applied after the Coolidge ray exposure and thus determine if the cause is a simple one or more complex as has been discussed by Mr. J. A. Capp. Since making these suggestions to Messrs. Waring and Hofammann I have not been advised of any further developments, but further thought has strengthened my belief in the usefulness of this means of detection, both before, during and after use.

Quite apart from detection we have quite definitely concluded for gun steel that melting and ingot practice on well-known sound principles avoids practically all of the difficulty.

Mr. Unger. MR. J. S. UNGER (*presented in written form*).—The authors have shown some interesting examples of the effects of hot concentrated acid solutions in etching rails, tires and wheels, and conclude by saying they believe the defects discovered have their origin during the manufacture of the material. Whether such criticism is justified and whether the so-called defects are injurious, remains to be proven.

Deep etching by strong solutions is not new. Bessemer rail sections were etched in 1.20 nitric acid for 15 to 20 minutes at least 25 years ago. Our recent investigations with slightly warm, much more dilute solutions than described in the paper, the action being prolonged for 24 hours, give very much clearer definition and less exaggeration than is shown by the action of the stronger solution. Strong solvents cannot be recommended

Mr. Unger.

for etching, as their action is so powerful as to tend to dissolve the entire specimen, and if sponginess exists to apparently increase it, rather than differentiate between portions of slightly different solubilities.

We have investigated and are still continuing work to determine the rate of acid attack in the three dimensions of the rail, the transverse vertical from a disk section taken from the end of the rail, the horizontal longitudinal, taken from a disk section at the interior or under side of the longitudinal slab, and the vertical longitudinal disk section, taken from the interior of a longitudinal slab, cut from the side of the rail.

In the few experiments we have been able to make to date, we find the action of the acid is about four times as rapid in the transverse vertical disk, or that from the end of the rail, as on either of the longitudinal specimens. When such specimens of the same area, taken from the same rail, and as closely adjacent as possible, are immersed in the same solvent, at the same time, the difference is apparent at once by the rate of evolution of the gas. If transverse sponginess exists in a rail which is not visible to the eye or under the microscope, and this be developed by the etching solution and the action of the solvent is four times as great in one direction as in another, the extent of such sponginess is greatly magnified, leading to erroneous conclusions as to the extent of the supposed defect.

Differences in appearance at different parts of a section after etching of rolled or forged material are to be expected, and occur in all steels. The flow lines of the metal during work, while in a plastic condition, the greater density of the outer portion which received the most work and was cooled more rapidly, and the sponginess at the interior having less work and slower cooling, are always apparent. This difference in appearance may mislead those who are not familiar with how the specimen should look and cause them to place a wrong construction on the evidence.

A certain railroad has purposely removed several good rails from the track and cut them up for examination. Of these good rails, some were found to show supposed defects after etching, others were free from such defects. All showed longitudinal lines in the direction of rolling. Additional rails were removed from the track which were defective, some having transverse

Mr. Unger. fissures. These were etched and were practically the same as the etchings from the good rails.

In the face of such conflicting evidence, it appears unwise to draw any conclusions as to the detrimental character in service of a rail which has shown sponginess during etching.

The only solution to the question as it now stands, would be to take a number of new rails and etch them, separate them into two classes, supposedly "good" and supposedly "bad," put them into the same service at the same time, alternating the rails as laid, and from their average track service determine which ones are good and which bad. Until that is done, we do not have sufficient evidence to warrant drawing conclusions.

Mr. Bronson. MR. C. B. BRONSON (*presented in written form*).—Since Mr. Waring first informed rail investigators of his interesting disclosures in the deep etching of rail steel, we have taken an active and decided interest in the work. In addition to ordinary deep etching of numerous specimens of rail heads, both new and failed, we have attempted to determine the nature of these developed defects by means of various experiments with a particular object in mind for each.

Some work conducted has shown that annealing of full-size rail heads at 1000° C. for $4\frac{1}{2}$ hours and then furnace-cooled did not remove the condition or state for the development of cracks, for deep etching made on a half section of the rail head disclosed cracks similar to those developed on adjacent unannealed samples from the same rail head. The time and temperature of soaking may not have been sufficient to readjust the interior structure of the rail head to prevent attack from deep etching solutions.

Some measurements have been made under the microscope of the width of the cracks when etched in HCl for 30 minutes at 180° C. The width varies considerably for any crack; in some places only a very small opening is noticeable. The ends of the cracks have rounded edges generally, while the path of a crack through the metal is a very irregular line.

We also attempted to rearrange and readjust and destroy the original crystallin structure of the mass of the rail head by forging, and thus destroy the conditions for attack when deeply etched. Our work is somewhat limited in this respect, but there are indications that forging will eliminate the original structure of the steel and prevent cracks under the etching attack. **Mr. Bronson.**

We have made experiments recently to locate the zones of metal which succumb to deep etching, without the necessity of destroying the evidence contained within the material which is eaten out by the acid. We therefore took short pieces of rail heads, polished vertical half sections through the head, which were then sprinkled with fine iron filings and magnetized. We anticipated that the action of magnetizing the piece of rail steel would force the filings, due to polarity, to arrange themselves in lines or groups according to the location of the undeveloped cracks, thus disclosing their identity,—an ideal condition for study under the microscope. While we have only had partial success so far in this line, we intend to continue the study, for it is decidedly important to locate the sources of cracks without the necessity of resorting to deep etching to disclose their position.

Measurement and microscopic study to date indicate that deep etching cracks in rail steel are in effect hot-short zones of metal, which rupture when rolled below a proper temperature, and are chilled and embrittled further by rapid cooling on the hot beds, combined with the shattering action or tendency of gagging on the metal of the rail.

Intensive study in the near future should throw enough light on the problem to settle its origin and suggest the remedy, as in the case of reheated blooms for interior transverse fissures.

Mr. Wickhorst. MR. M. H. WICKHORST.—Messrs. Waring and Hofammann are to be congratulated for so effectively using what may perhaps be an old method, for bringing out new information. A transverse fissure in the interior of a rail head is a growth in service, proceeding from a granular "core" or "nucleus." The nature and origin of the nucleus has been somewhat of a puzzle, although there has been some information that it is an internal crack, acting as the starting point for the growth of a fissure, and the work of Messrs. Waring and Hofammann confirms this view in a very clear manner. The next objective in the trail of this investigation is to determine the reason for the internal shattering of the steel in the rail head and to apply a remedy.

Mr. Force. MR. H. J. FORCE.—The paper by Messrs. Waring and Hofammann brings out certain lines along which to work that

Mr. Force. we have not had up to this time. We have been studying the rail situation for twelve years or better, and during that time we have discovered, just as every one else has, that a certain lot of rails from a certain mill will develop transverse fissures and another lot from the same mill will not develop transverse fissures. The question has been raised as to whether or not these rails were overloaded. The authors' paper shows clearly that the defects in the rails are for the most part in the center of the rail and not on the side. This led us, in our investigation, to the conclusion that the trouble was due to the manufacture of the steel. It was clearly shown that the steel from which a rail developing transverse fissures was made had not been held a sufficient length of time in the ladle. When the steel has been held nine or ten minutes in the ladle, a much better rail is produced than when the steel is held one or two minutes. There may be instances where rails from steel held nine or ten minutes in the ladle have shown transverse fissures, but if so, we have not found any up to the present time, and our experience goes back several years.

I think, therefore, that we should determine the effect of holding steel in the ladle for one or two minutes up to say ten minutes. In that connection, I should like to ask Mr. Waring, referring to the new rail mentioned in the paper, whether he knows how many minutes that steel was held in the ladle before it was poured into the ingots.

Mr. Waring. MR. WARING.—I am sorry I do not have that record.

Mr. Job. MR. ROBERT JOB.—I have been very much interested in this paper, and there are one or two questions I should like to ask Mr. Waring. First, has he made any tests upon new rails in order to find out whether cracks developed under different conditions of cooling; that is, taking slow cooling on the one hand and quick cooling on the other hand? And also, has he found any cracks develop when rails are suddenly chilled; that is to say, with the idea of finding out whether, with heat treatment of rails, cracks of this kind would be likely to be shown under those conditions of testing?

Mr. Waring. MR. WARING.—In reply to Mr. Job, I am sorry to say that our investigation has not yet proceeded far enough to enable us to answer the questions he has brought up. We hope to continue the work so that we will be able to answer such questions.

MR. G. AERTSEN.—In this most interesting paper it seems to me that one of the most important paragraphs is the last one, in which it is stated that, "We are inclined to believe that the cause must be sought in the mill during some stage in the process of fabrication of the material." **Mr. Aertsen.**

Two points have been emphasized in the discussion so far. One is the impossibility of making good steel from bad ingots; the other is the possibility of making bad steel from good ingots. In an experience of some years, I have often tried unsuccessfully to do the first and to avoid doing the latter.

Without considering the question of whether this deep etching or excessive pickling, or whatever one chooses to call it, puts defects in the metal that did not exist before, I should like to call special attention to Figs. 5 and 6 of the paper, which show the results of etching on sections from tires. We all know that in rolling in a bar mill we sometimes get "fish tail" ends, showing that the outside strata have been elongated in the process of rolling more than the internal portion of the metal. If we imagine the bar a ring, and these fish tails together or attached, we get an included vacuum, if I may call it so, which in a rolled ring is somewhere in the interior of the metal.

It is interesting in these two figures to notice that the defects or cracks do not appear near the outside circumference or the inside circumference of the ring. They are in the interior of the metal to which I have referred, and when we realize that in the process of rolling a tire we are stretching the internal diameter about 20 per cent less than the external diameter, if we have imagination enough we can see what is happening to the metal in the interior.

There are two big factors in that rolling: one is the draft or amount of reduction, the other is the speed of reduction. They are both very important, and if we realize that in rolling a ring like a tire, all of the reduction has to be made practically in one pass by continuing or increasing the pressure, instead of leading from one pass to another, as we do in a rail mill or a structural mill or a bar mill, where the percentage of reduction is calculated and fixed, I think it raises some very interesting questions.

From personal experience, I know that defects, cavities,—not "incipient cracks," but cavities that you can put your fist

Mr. Aertsen. in, pretty nearly,—can be developed in perfectly sound steel by improper methods of heating and rolling, if the section rolled is elongated in strata or layers as I have tried to describe.

Mr. Force. MR. FORCE.—About a year and a half ago we had occasion to remove an entire heat of rails from our tracks. Several of the rails developed transverse fissures. All the rails were brought into the shop and broken up. Only about 25 or 30 per cent of the entire lot showed evidence of transverse fissures, which tends to support the statement I have made, that the first ingots poured from a heat are the ones possibly that develop the transverse fissures, while those poured later, after the steel has stood in the ladle and the reaction has been completed, are possibly the ones producing rails more free from transverse fissures.

Mr. Comstock. MR. G. F. COMSTOCK (*by letter*).—The authors of this paper do not seem to have taken into consideration the fact that almost any steel or other metal is normally subject to fissuring or cracking when strongly corroded by certain chemical reagents while in a badly strained or cold-worked condition. The paper of H. Baucke "On the Action of Electrolytes on Metals under Stress,"[1] describes instances of this kind in steel, and the cracking of strained brass when attacked by ammonia or certain salts is another similar instance. That steel rails which have failed from transverse fissures should be subject to cracking in this way when strongly attacked by acids is not surprising in view of the quite well established theory that transverse fissures are due, in part at least, to internal strains. The fact that some used rails have been found in which cracks could not be so produced is more surprising, and leads to the inference that such rails had been so supported in track that they were strained much less than usual. The development of these etching cracks in new rails merely shows a state of strain, or a cold-worked condition in them also, which has long been recognized as almost inevitable with present methods of cooling and straightening.

It cannot of course be maintained that fine internal cracks, both transverse and longitudinal, do not sometimes exist in rails; but when such cracks are present they should be capable of recognition after light etching, or in a properly prepared specimen

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[1] *Proceedings*, Inter. Assoc. Test. Mats., Sixth Congress, 1912, Second Section.

Mr. Comstock.

for microscopic examination. The method of very strong and deep attack by hot acid described by the present authors would seem of less value, since it does not distinguish between (1) cracks actually existing in the metal and recognizable as such through the microscope; (2) the cracks or fissures artificially produced, so to speak, in strained metal by the attack of the very reagent used in their investigation; and (3) narrow streaks of more soluble metal in segregated steel, due to local abundance of sulfide inclusions which cause deep pits after severe etching. On the other hand this method may be of value when applied with discretion to steel known to contain no segregated sulfides, in giving an estimate of the strained condition of a rail or forging; and although less reliable than the standard method for this test, involving very accurate measurements before and after careful machining, it is doubtless very much easier to use.

SOME FATIGUE TESTS OF NICKEL STEEL AND CHROME-NICKEL STEEL.

By H. F. Moore and Arthur G. Gehrig.

SUMMARY.

The paper gives a report of tests of nickel steel of about 3.3 per cent nickel content and of chrome-nickel steel with about 0.8 per cent chromium and 1.3 per cent nickel. Both static tension tests and tests under reversed bending stresses were made.

Tests were made of annealed material, of heat-treated material, and of specimens with polished surface.

The test results indicate that the results of a static tension test are not a reliable index of fatigue strength of a material under oft-repeated low stresses, and that high-stress, short-time fatigue tests do not give a reliable index of fatigue strength under oft-repeated low stresses.

The test results indicate also that a heat treatment may raise the elastic strength of a steel without increasing its fatigue resistance under low stresses.

The tests also indicate that perfection of surface finish is an important factor in determining fatigue resistance under oft-repeated low stresses.

SOME FATIGUE TESTS OF NICKEL STEEL AND CHROME-NICKEL STEEL.

BY H. F. MOORE AND ARTHUR G. GEHRIG.

This paper gives the results of a series of tests made in the Materials Testing Laboratory of the University of Illinois as an introductory study of the effect of heat treatment on fatigue-resisting strength of steel. Although the tests constitute a preliminary series, certain indications given by them are judged to be of sufficient interest for publication at this time.

DESCRIPTION OF TESTS.

Materials.—Two kinds of steel were studied, one a nickel steel and the other a chrome-nickel steel. The chemical composition of samples of each is given in Table I. The specimens of nickel steel were cut from unstressed portions of test plates furnished some years ago for a series of tests on nickel-steel riveted joints,[1] and the material for these plates was carefully selected with a view to uniformity. The specimens of chrome-nickel steel were obtained from one bar of steel $1\frac{3}{4}$ in. in diameter, which was drawn hot under a hammer to $\frac{3}{8}$ by $\frac{3}{4}$ in. in cross-section.

TABLE I.—CHEMICAL COMPOSITION OF MATERIAL.

	NICKEL STEEL.	CHROME-NICKEL STEEL.
Carbon, per cent	0.258	0.346
Manganese, per cent	0.700	0.625
Phosphorus, per cent	0.044	0.021
Sulfur, per cent	0.008	0.047
Silicon, per cent	.....[a]	0.245
Nickel, per cent	3.330	1.300
Chromium, per cent	.....	0.844

[a] Silicon content not determined.

Heat Treatment.—All specimens were first annealed, the nickel steel specimens from a temperature of 1320° F. (716° C.), and the chrome-nickel specimens from a temperature of 1425° F. (774° C.). Some specimens were tested annealed; other specimens were first annealed as above and then were given one of two different heat treatments, known as heat treatment "H" and heat treatment "K" respectively. In heat treatment "H" the metal is heated to a temperature of 1550° F. (843° C.), quenched in fish oil at room temperature, reheated to 900° F. (482° C.), and cooled slowly in charcoal. In heat treatment "K" the material is heated to 1525° F. (835° C.), quenched in fish oil, reheated to 1350° F. (832° C.), quenched in fish oil, reheated to 900° F. (482° C.), and cooled slowly in charcoal.

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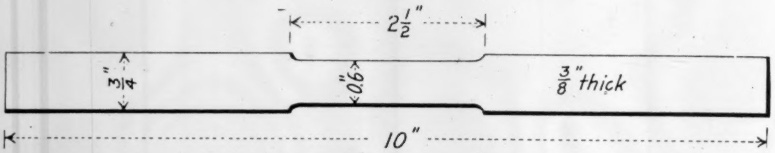
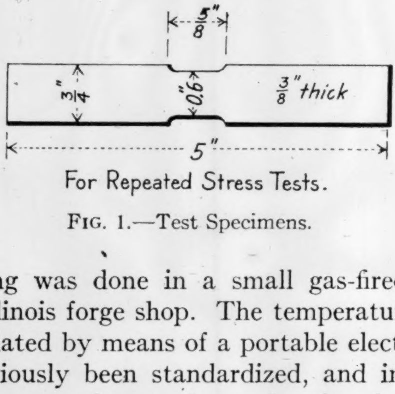
[1] See *Bulletin No. 49*, Engineering Experiment Station, University of Illinois.



For Static Tension Tests.

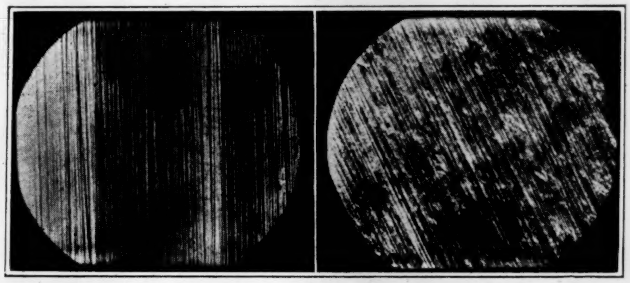


For Repeated Stress Tests.

FIG. 1.—Test Specimens.

All heat treating was done in a small gas-fired oven in the University of Illinois forge shop. The temperatures were determined and regulated by means of a portable electric pyrometer, which had previously been standardized, and in making heat treatments care was taken to have the tip of the pyrometer couple in contact with the metal in the furnace.

Specimens.—The form and size of test specimens used are shown in Fig. 1. The specimens used for fatigue tests were subjected to flexure, and were slightly reduced in cross-section at the center. This reduction of area causes some irregularity of stress at the shoulders but is believed to cause less irregularity than is caused by the heavy localized stress where the jaws of the machine grip the specimen. In a specimen not reduced in section between jaws the maximum stress comes where the jaws grip the specimen; in a specimen reduced in section between jaws the maximum stress comes at the reduced section. For most of the specimens the surface was left in the condition resulting from the last heat treatment. In no case was there serious scaling. For some of the specimens the surface was polished. The direction of polishing was parallel to the longitudinal axis of the specimen. The polish used for certain nickel steel specimens consisted of four steps: (1) grinding on a coarse emery wheel, (2) grinding on an emery-filled buffer, (3) grinding on a buffer filled with crocus composition and (4) grinding on a dry felt buffer. The polish used for certain chrome-nickel steel specimens involved three steps: (1) grinding on a coarse emery wheel, (2) grinding on a medium-grain emery wheel and (3) grinding with a fine-grain oil-filled emery wheel. The second method gave a distinctly smoother polish than did the first method. Both polishes were good shop polishes; neither gave a smooth "flowed surface" such as is necessary for metallographic specimens. Fig. 2 gives photomicrographs of surfaces with the two polishes.



(*a*) (*b*)

FIG. 2.—Photomicrographs of Surfaces of Two Test Specimens. (*a*) Surface of Polished Nickel Steel Specimen; (*b*) Surface of Polished Chrome-Nickel Steel Specimen.
Magnification, × 50.

Testing Machines.—Tension tests of samples of the material were made in a Riehle 100,000-lb. universal testing machine. In the tension tests a Riehle extensometer with a gage length of

2 in. was used, and a stress-strain diagram plotted for each test. From this stress-strain diagram was determined the proportional limit, and the "useful limit."[1]

The repeated stress tests were made in an Upton-Lewis repeated stress testing machine. In this machine the specimen is subjected to reversed bending stress. The bending moment applied to the specimen is resisted by the compression of a pair of calibrated springs, and the amount of this compression is recorded on a diagram, which thus measures bending moment and nominal fiber stress in the specimen. The length of diagram measures the number of reversals of stress required to fracture the specimen, and this number is also recorded on the dial of a revolution counter. For the earlier tests this machine operated at a speed of 250 vibrations per minute, for the later tests it operated at a speed of 276 vibrations per minute. In view of test results obtained in British laboratories which indicate that for small specimens speed of repetition of loading makes little difference in fatigue test results up to 2000 repetitions per minute, a variation from 250 to 276 vibrations per minute seems to have no significance.

TEST DATA.

Table II gives the results of the static tension tests of specimens of the materials tested, and Table III gives the results of the fatigue tests under repeated stress.

Figs. 3, 4, and 5 show graphically the results of the fatigue tests under repeated stress. Each of these figures is in two parts: one in which values of fiber stress and reversals for failure are plotted to ordinary coordinates, and the other in which logarithmic coordinates are used. In a paper[2] before this society presented in 1910, Prof. O. H. Basquin of Northwestern University called attention to the fact that available test data for repeated stress tests showed that over a considerable range the relation between nominal fiber stress in a specimen (S) and number of repetitions necessary to cause failure (N) was given closely by the equation

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[1] The "useful limit" was first used as a criterion of elastic strength by the A.S.C.E. Special Committee on Steel Columns and Struts (see *Transactions*, Am. Soc. C. E., January 16, 1918.) It is determined by drawing tangent to the stress-strain curve a line having one-half the slope of the straight portion of the stress-strain curve. The useful limit is the stress corresponding to the point of tangency between the line and the stress-strain curve.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. X, p. 625 (1910).

$$S = \frac{B}{N^q} \quad \text{or} \quad \log S = \log B - q \log N$$

in which B and q are experimentally determined constants. If the above equation holds, when values of S and N are plotted to logarithmic coordinates the graph is a straight line.

Without taking the time to discuss the limitations of this formula, it may be pointed out that the study of fatigue-resisting qualities of a material for various intensities of stress may be studied from a S-N diagram, and that such a diagram plotted to logarithmic coordinates, giving straight-line graphs, furnishes a very convenient comparison of fatigue-resisting properties for different stresses. The ordinates of such diagrams for any value of N gives the relative strength of materials for a given length of life, and the relative slope of the straight line graphs shows at a glance the relative strength of materials for short-time service and for long-time service. In this respect a S-N diagram gives more information as to the fatigue-resisting qualities of a material than does a series of tests at some arbitrarily chosen standard fiber stress.

TABLE II.—RESULTS OF STATIC TENSION TESTS.

EACH VALUE IS THE AVERAGE OF TWO OR MORE TEST RESULTS.

Tensile Properties.	Nickel Steel.				Chrome-Nickel Steel.		
	Annealed.	Heat Treatment "H."	Heat Treatment "K."	Heat Treatment "K" and Polished.	Annealed.	Annealed. and Polished.	**Heat Treatment "H."**
Proportional limit, lb. per sq. in.	45 500	99 500	88 200	83 500	33 800	39 700	**138 000**
Useful limit, lb. per sq. in.	49 900	107 700	91 500	89 000	36 000	42 200	**144 800**
Tensile strength, lb. per sq. in.	80 800	130 700	107 400	115 200	86 600	91 600	**169 000**
Elongation in 2 in., per cent	32.0	19.5	23.5	21.5	23.7	21.0	**11.0**
Reduction of area, per cent	58.5	58.0	61.0	59.0	49.7	47.0	**43.5**

In the logarithmic diagrams in Figs. 3, 4, and 5 the straight line plotted for any material is the "most probable" straight line to fit the test data for that material. The ordinates and slope of this "most probable" straight line were determined by the method of least squares.[1]

TABLE III.—RESULTS OF REPEATED STRESS TESTS.

NOMINAL FIBER STRESSES ARE COMPUTED BY MEANS OF THE USUAL FLEXURE FORMULA.

Nickel Steel Specimens.		Chrome-Nickel Steel Specimens.	
Nominal Fiber Stress, lb. per sq. in.	Number of Reversals for Failure.	Nominal Fiber Stress, lb. per sq. in.	Number of Reversals for Failure.
ANNEALED SPECIMENS.			
69 000	10 900	50 800	**43 400**
58 000	35 600	43 200	**113 500**
42 000	166 600	35 700	**148 300**
37 000	4 464 000	33 300	**190 400**
28 000	1 540 000	31 700	**230 600**
		23 500	**564 900**
		17 800	**3 935 100**[a]
HEAT TREATMENT "H."			
98 200	15 000	141 800	**6 700**
81 400	52 700	123 800	**14 300**
62 200	86 900	101 700	**26 700**
43 600	216 100	76 500	**53 300**
37 800	2 083 000	51 000	**140 100**
		29 600	**353 500**
		19 100	**4 350 000**[a]
HEAT TREATMENT "K."		ANNEALED SPECIMENS, POLISHED.	
91 700	15 600	49 400	**30 000**
74 600	55 200	48 800	**92 300**
51 200	103 300	42 500	**286 800**
48 500	167 300	38 300	**167 500**
42 700	182 300	33 000	**466 300**
		28 400	**597 300**
		25 400	**7 900 000**
HEAT TREATMENT "K" FOLLOWED BY POLISHING.			
96 000	12 100		
76 800	37 800		
47 000	228 200		
44 200	296 900		

[a] Specimen not broken.

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[1] See Tuttle, "The Theory of Measurements," p. 240.

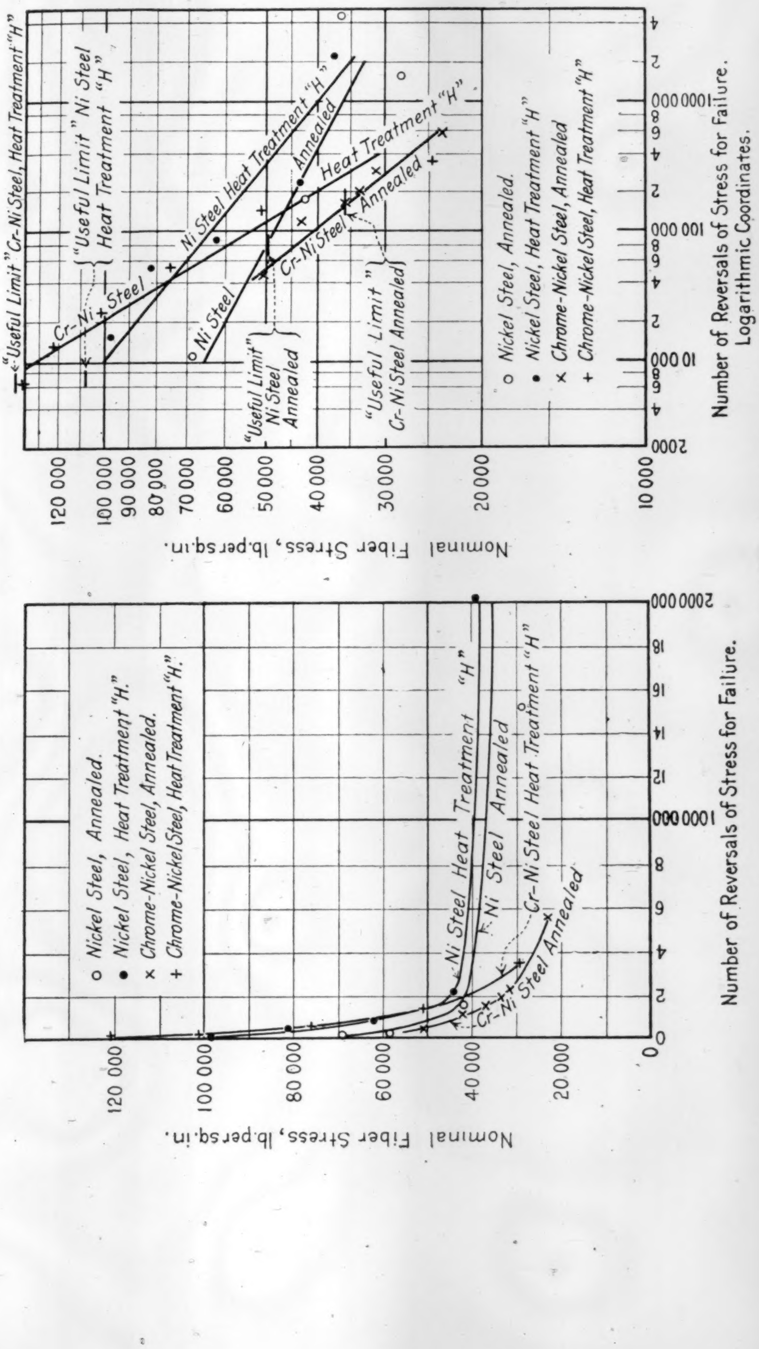

FIG. 3.—*S-N* Diagrams for Nickel Steel and Chrome-Nickel Steel.

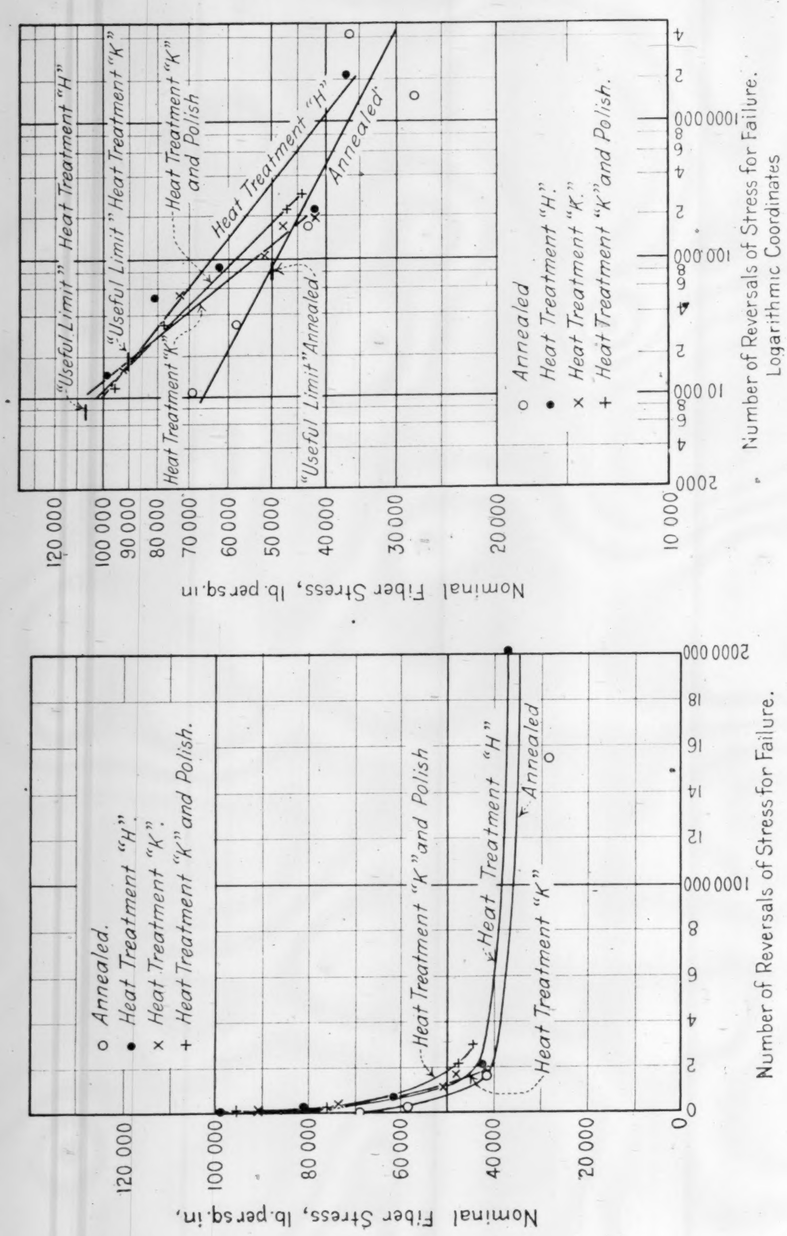

FIG. 4.—*S-N* Diagrams for Nickel Steel.

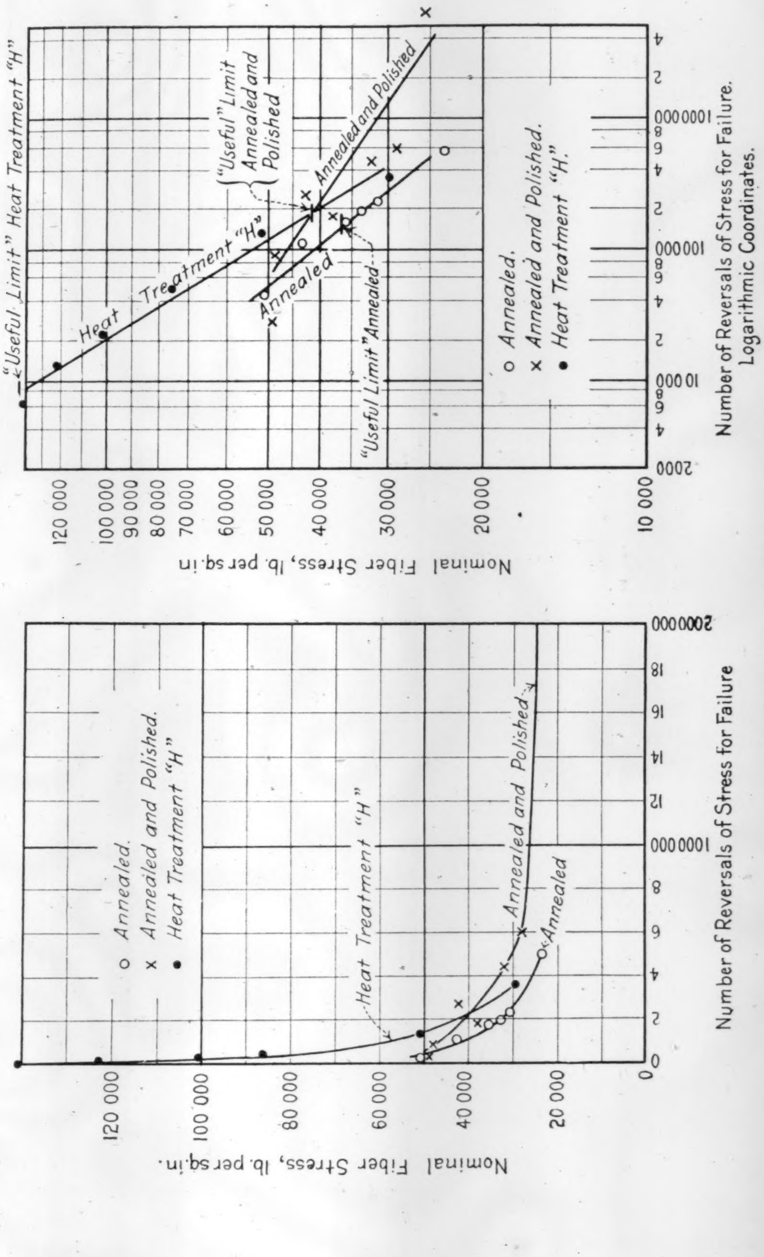

FIG. 5.—*S-N* Diagrams for Chrome-Nickel Steel.

DISCUSSION OF RESULTS AND CONCLUSIONS.

The test results indicate that static elastic strength (as indicated by the proportional limit or the "useful limit") is not a reliable index of fatigue-resisting strength under repeated stress. As shown in Fig. 3 the specimens of chrome-nickel steel, both the annealed specimens and the heat-treated specimens, showed higher proportional limits and "useful limits" than did the corresponding specimens of nickel steel, but the nickel steel specimens gave longer endurance under repeated reversals of low fiber stress than did the corresponding specimens of chrome-nickel steel. For both nickel steel and chrome-nickel steel the heat treatments used raised the proportional limit, the "useful limit" and the tensile strength in a marked degree, but the heat treatments added but little to the fatigue resistance under repeated reversals of low stress. Figs. 3, 4, and 5 illustrate the above points.[1]

A repeated stress test using very high stresses, with consequent small number of repetitions for failure, cannot be relied on to give an index of the fatigue-resisting power of a material under a large number of repetitions of small stress. This is illustrated by Fig. 3. An examination of that figure shows that if a fatigue test of specimens of the chrome-nickel steel and of nickel steel were made using a nominal fiber stress of 100,000 lb. per sq. in., the chrome-nickel steel would give the better results; if a fatigue test were made using a nominal fiber stress of 40,000 lb. per sq. in. the reverse result is given.

In connection with the above paragraphs these test results should not, of course, be interpreted to mean that chrome-nickel steel is, in general, inferior in fatigue resistance to nickel steel. These tests give values for the two lots of steel tested, and it should be remembered that the original bar of chrome-nickel steel was worked down to small size under a forge shop hammer. Injury to the structure of the material may have been done in that process.

The tests also indicate that a given heat treatment may give high elastic static strength to steel without proportionately increasing its resistance to fatigue under repeated stress. This is shown by the convergance of the graphs for heat-treated steel and for annealed steel shown in Figs. 3, 4, and 5. Here again a warning should be sounded against drawing from these tests the general conclusion that all heat treatment is ineffective in increasing the resistance of a material to fatigue under repeated stress. The test results apply only to the particular conditions of heat treatment actually given to the specimens tested, but they do furnish an illustration of heat treatment which raised static elastic strength without proportionately increasing resistance to fatigue under reversals of low stresses.

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[1] See also results for cold-worked steel, Moore and Putnam, "Effect of Cold-working and of Rest on Resistance of Steel to Fatigue under Reversed Stress." *Transactions*, Am. Inst. Min. Engrs., February, 1919. Also results for manganese bronze, Corse and Comstock, "Aluminum Bronze, Some recent Tests and Their Significance," ***Proceedings*, Am. Soc. Test. Mats., Vol. XVI, Part II, p. 118 (1916).**

At first thought it would seem that any structural damage done by heat treatment or any structural imperfections present in metal would act to cause yielding under low stress and would give a low proportional limit in a static test of the material. It should be remembered, however, that in any determination of any kind of a statically determined "elastic limit" the elastic breakdown is indicated by the effect on the stretch over a considerable length of specimen. Considerable local damage could be done over a microscopic area without affecting the stretch over the length of the specimen to such an extent that extensometer readings would be appreciably affected. Such local damage over a microscopic area, whether caused by an internal flaw or external surface irregularity, may, however, start a progressive fatigue failure of the material although it may not cause sufficient yielding of the specimen as a whole to affect appreciably an extensometer reading. An illustration of this local damage is furnished by the "snowflakes" sometimes found in steel, which do not seem to affect the static elastic strength of the steel, but are recognized as dangerous defects.

A high static elastic strength is of indirect advantage in materials subjected to repeated stress, even if it is not accompanied by increased endurance under repeated low stresses. Practically every machine member or structural part is subjected to occasional loads above the normal. If the material has a low static elastic strength such an overload may cause plastic action in parts of the member, and such plastic action (cold-working) tends to weaken the fatigue-resisting power of the material.[1] If the material has a high elastic strength, while micro-flaws may be spreading slowly, yet under an occasional overload the spread of micro-flaws is not abnormally hastened by the formation of plastic material.

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[1] Moore and Putnam, *loc. cit.*

The tests herein reported indicate that perfection of surface finish is an appreciable factor in developing resistance to fatigue under repeated stress. This is shown by the divergance of the graphs in Figs. 4 and 5 for polished specimens from the graphs for the corresponding unpolished specimens. The superiority in fatigue resistance of the polished specimens over unpolished specimens *increases* as lower test stresses are used. This superiority may be explained as follows: the nominal fiber stress in a machine or structural member, computed by the ordinary flexure formulas, does not take into account any localized stresses due to irregularity of surface or outline, yet both mathematical analysis and direct experiment indicate that over microscopic areas such localized stresses may be large.[1]

The nominal fiber stress in a test specimen gives a fairly reliable basis for comparative tests, but, in all probability, does not give an accurate measure of the magnitude of the maximum localized stress in the specimen. Surface irregularities, especially sharp grooves and scratches, may cause high localized stresses, and microscopic cracks may start at such grooves or scratches, and, gradually spreading, cause eventual failure. It cannot be definitely stated that any machine or structural member is absolutely safe from the possibility of such failure if stresses are repeated often enough. It has been shown that the endurance of a repeated stress test specimen is appreciably lowered when on its polished surface a needle scratch is made.[2] Good surface finish free from tool marks, and generous fillets at corners, are vital factors in prolonging the life of machine parts subjected to repeated stress.

Fatigue failure under repeated stress is a progressive failure starting in nearly all cases from some defect or irregularity either of internal structure or external surface. Freedom from internal flaws and surface irregularities is far more important in members subjected to repeated stress than in members subjected to but few repetitions of load.

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[1] See article by Preuss, *Zeit, d. Ver. Ing.* Part 8, p. 664, 1913. Results summarized in Fifth Edition of Johnson's "Materials of Construction" (rewritten by Withey and Aston), p. 663.

[2] See paper by Eden, Rose and Cunningham, *Proceedings*, Inst. of Mech. Engrs. (British), **Parts 3 and 4, p. 839 (1911).**

DISCUSSION.

Mr. Dix.

Mr. E. H. Dix.—I should like to call attention to some tests I made in 1916 at Cornell University on the same type of testing machine as used by the authors. The tests, however, were on aluminum bronze (10 per cent aluminum), not steel. We found the same thing to be true as the authors have found, namely, that a heat treatment which will increase the properties of aluminum bronze as obtained by the static tension test, including the proportional limit, will also increase the resistance to fatigue when tested at high stresses; but when tested at low stresses, the heat-treated material will not resist fatigue as well as the material as cast. I think this is of interest, inasmuch as it shows the same thing to be true of a non-ferrous material that the authors have found to be true of the steel mentioned in their paper.

Mr. Ruder.

Mr. W. E. Ruder.—In the first place, I should like to call attention to the fact that the authors in their paper have referred to tests in reversals, and in a previous paper I think they referred to tests in cycles. This causes some confusion in the interpretation and comparison of tests, and I think some standard method of reference ought to be arrived at.

In a series of tests which we are carrying out now at the Research Laboratory on 3.5-per-cent nickel steels, on the same type of machine, the results are in general about the same as those found by the authors at high stresses; but the logarithmic curves for the same kind of steel under different heat treatment are practically all parallel and do not cross at such decided angles as the authors show them. The only heat treatment which we have found to cause these curves to cross has been the blue heat treatment, which we have been investigating for the National Research Council. Most of the results, therefore, for low stresses have decidedly different values than those given by the authors. I hope at some future time to publish these results for more direct comparison with their results.

Mr. Abbott.

Mr. R. R. Abbott.—I do not quite understand some of the conclusions drawn from the data given in the table and in

Mr. Abbott. the figures of the authors' paper. As an illustration, take the left hand diagram in Fig. 4: the almost horizontal line "H" is drawn through two points, one at 200,000 and one at 2,000,000; the lower line is drawn from apparently three points, one at 200,000 and one quite low at 1,600,000 and one not shown on the figure at four or five million. It does not seem to me that the data justify the conclusion that heat treatment shows very slight improvement over the annealing. The lower curve goes nowhere near the lowest point shown on the figure. Suppose we draw a horizontal line through the two lower curves and from the points of intersection of it with the curves drop vertical lines to the abscissa; at almost any place you will find that the heat treatment gives three times the efficiency under repeated stresses that the annealing does. If we draw the lower line using the same figures and working it out according to least squares, I find that the second curve gives an efficiency for heat treatment much more decided than in the curves shown. Now we know from experience that heat treating, even when drawing back at a very high temperature and getting a very soft steel, but still having a uniform material rather than a dissimilar conglomeration of ferrite and pearlite, gives an enormous increase in fatigue-resisting power, and it is a new idea to me that heat treatment does not increase endurance. I wish to state that heat treatment increases the fatigue-resisting power of steel enormously. The tests shown simply indicate that this particular heat treatment did not increase this power much over three times.

Messrs. Moore and Gehrig. MESSRS. H. F. MOORE AND A. G. GEHRIG (*Authors' closure by letter*).—The authors wish to acknowledge the force of Mr. Ruder's distinction between the terms "reversals" and "cycles" of stress. Cycles of stress are referred to throughout the paper. Mr. Ruder's remarks also give an interesting illustration of heat treatment which apparently did increase the fatigue-resistance of steel under low stress.

Mr. Abbott confined his discussion to one heat treatment shown, and does not consider the logarithmic diagram. Studying the graph for heat treatment "K" in Fig. 4, it is seen that the graph for the heat-treated specimens *intersects* the graph for the annealed specimen. Evidently this particular heat treatment was not effective in increasing fatigue-resistance for stresses

Messrs. Moore and Gehrig.

below that at the intersection of the graphs. The effectiveness of heat treatment, or any other process, in increasing the fatigue resistance of steel may be expressed in either of two ways: (1) by comparison of the nominal fiber stress under which failure occurs for a given number of cycles of stress, or (2) by a comparison of the number of cycles of stress necessary to cause failure under a given nominal fiber stress. The two methods yield quite dissimilar numerical results from the same test data.

The following table is compiled from the graphs in the paper and shows the effects of heat treatment for the specimens tested by the writers, the effectiveness of heat treatment being expressed in both the above ways. The decreased effectiveness of these particular heat treatments in adding fatigue resistance under low stresses is evident.

EFFECTS OF HEAT TREATMENT ON FATIGUE RESISTANCE.

Material and Heat Treatment.	Per cent of Increase Over Annealed Steel of Nominal Fiber Stress Required to Cause Failure of Heat-Treated Steel After the Numbers of Cycles Indicated at the Head of the Columns Below.				Per cent of Increase Over Annealed Steel of Number of Cycles Required to Cause Failure of Heat-Treated Steel Under Nominal Fiber Stresses Given at the Head of the Columns Below.		
	Static Tests.[1]	10 000	100 000	1 000 000	60 000	50 000	40 000
Nickel Steel:							
Heat Treatment "H"..	115	56	30	12	580	320	140
Heat Treatment "K"..	78	62	10	...[a]	220	44	...[a]
Chrome-Nickel Steel:							
Heat Treatment "H"..	300	58	32	14[b]	150	120	90

[1] Measured by useful limits. [a] Decrease. [b] Estimated.

As pointed out by Mr. Abbott, there seems to be a considerable amount of qualitative evidence from results in practice to show that proper heat treatment increases the fatigue resistance of steel. It is to be hoped that there may soon be available test data to afford a basis for the quantitative measurement of the improvement of fatigue resistance given by such heat treatment, and that reliable commercial tests may be devised to distinguish between efficient and inefficient methods of heat treatment designed to increase resistance to fatigue.

It was not the intention of the authors of the paper to make any claim that chrome-nickel steel is not as good as nickel steel

Messrs. Moore and Gehrig.

or that heat treatment in general is not effective in raising fatigue strength. They wish to report the results of two series of tests which they think give certain interesting indications. Those indications are that a statically determined elastic limit of material *may* be raised by heat treatment or by a different chemical composition without increasing the fatigue strength of the material under long-time, low-stress tests, and that deductions as to fatigue strength under long-time, low-stress tests or service cannot always be made from short-time, high-stress tests,—tests which involve bending or twisting of specimens well beyond the yield point.

The authors wish to point out that surface finish, either in a specimen or in a machine part, seems to play a decidedly important part in the resistance of the specimen or the machine part to fatigue stress. They wish to point out that when the term "fiber stress" is used, the quantity meant is the stress computed by the ordinary formulas of mechanics of materials, and that these formulas are based upon the assumption of homogeneity of material, and of definite application of load, which assumptions even in our most perfect test specimens—to say nothing of machine parts—are never exactly true. There always exists a multitude of localized high stresses extending over microscopic areas.

The authors wish to point out that these localized stresses may not affect the results of a static ordinary testing machine test. If the test is made with a delicate extensometer, the extensometer averages the deformation over the entire gage length, and a considerable variation over a microscopic area can take place undetected by the extensometer. These ordinary stresses are extremely useful in the computation of stresses for structures which are subjected to a comparatively few repetitions of load. They are useful in considering problems involving fatigue stress, because if the computed fiber stress is reduced, in general, the localized stress will be reduced. The authors wish to point out the importance of these localized stresses, and Figs. 5 and 6 of the paper on "Deep Etching of Rails and Forgings"[1] give a good illustration of material in which such localized stress would be high. Mathematical analysis, exten-

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[1] See p. 186.—ED.

Messrs. Moore and Gehrig.

someter tests of great sensitiveness, and tests with polarized light, all indicate that the stress at the edge of one of the cracks shown in those figures might be five or six times the computed stress across the rail at that section. This localized stress tends to cause the crack to extend. The extension of the crack would continue the intensification of stress, and fatigue failure might eventually result. The authors wish to call attention to the fact that we may have to change a great many of our fundamental views about the stresses which exist both in test specimens and in machine parts from views based on considerations of static loading.

THE INFLUENCE OF VERY LOW PERCENTAGES OF COPPER IN RETARDING THE CORROSION OF STEEL.

By D. M. Buck.

SUMMARY.

Previous work by the author indicated that copper in steel in amounts heretofore considered as only traces, materially influences the corrosion rate. In order to obtain further information, two heats of basic open-hearth steel were copperized in varying amounts from approximately 0.01 per cent up to 0.25 per cent. Sheets and test specimens from the various ingots were exposed to the weather for varying lengths of time, and the paper includes tables of chemical analyses and weight losses, as well as photographs and charts, showing condition of sheets and test specimens after exposure.

The following conclusions have been drawn from the results of this investigation:

1. Very low amounts of copper in steel materially lower the corrosion rate.

2. Steel with 0.03 per cent of copper corrodes only 60 to 70 per cent as fast as the same steel with 0.01 per cent of copper.

3. It has been customary to consider a copper content of any amount under 0.05 per cent as a trace, and it may be desirable to reinterpret many corrosion data obtained in work in which the effect of these minute amounts of copper has not been taken into account.

4. In order to leave an ample factor of safety, steel to resist atmospheric corrosion should contain not less than 0.15 per cent of copper.

5. Copper in amount of 0.12 per cent is sufficient to neutralize the influence of sulfur as high as 0.055 per cent.

6. Copper in amount of 0.15 per cent is sufficient to protect steels even if the sulfur content is considerably higher than normal.

THE INFLUENCE OF VERY LOW PERCENTAGES OF COPPER IN RETARDING THE CORROSION OF STEEL.

BY D. M. BUCK.

During the past twenty years, and more especially from 1913 to the present, numerous references have been made in literature to the influence of a copper content in steel and iron in retarding the corrosion rate. F. H. Williams[1] stated that copper in soft Bessemer steel lessened the corrosion when samples were alternately immersed in water and allowed to dry several times a day over a period of about one month. Stead and Wigham[2] reported series of tests made by immersing samples in the Middlesborough town water for a period of nine weeks. In the majority of cases the steels containing copper were superior from a corrosion standpoint. W. H. Walker[3] pointed out the marked influence of copper in lessening the solubility of steel in sulfuric acid. D. M. Buck[4] reported the results of a series of corrosion tests in which it was shown that when copper is present in steel to an extent of about 0.15 to 0.30 per cent, the corrosion rate under atmospheric conditions was greatly reduced.

Burgess and Aston,[5] in experimenting by adding various elements to pure electrolytic iron, found that the alloys with copper were less corrosive than the pure iron. Buck and Handy[6] corroborated the previous work of Buck on the influence of copper and found indications that very low amounts of copper affect the corrosion rate. E. A. and L. T. Richardson[1] concluded from their tests that "copper-bearing steels are decidedly superior to pure iron or charcoal iron" and that "the addition of copper to pure iron increases its resistance to corrosion but to no such extent as similar additions to steel." Kalmus and Blake[2] found that "the alloys formed by the

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[1] F. H. Williams, *Iron Age*, November 29, 1900.

[2] Stead and Wigham, *Journal*, Iron and Steel Institute (Great Britain), Vol. 2, p. 135 (1901).

[3] W. H. Walker, *Proceedings*, Am. Soc. Test. Mats., Vol. XI, p. 615 (1911).

[4] D. M. Buck, "Copper in Steel: The Influence on Corrosion," *Journal of Industrial and Engineering Chemistry*, June, 1913.

[5] Burgess and Aston, "Influence of Various Elements on the Corrodibility of Iron and Steel," *Journal of Industrial and Engineering Chemistry*, June, 1913.

[6] Buck and Handy, "Research on the Corrosion Resistance of Copper Steels," *Journal of Industrial and Engineering Chemistry*, March, 1916.

TABLE I.—ADDITIONS OF COPPER TO NORMAL BASIC OPEN-HEARTH STEEL.

Ingot No.	Additions of Copper, lb.	Copper Desired, per cent.
1	Not used	....
2	None	0.01
3	0.6	0.02
4	1.2	0.03
5	1.8	0.04
6	2.4	0.05
7	3.0	0.06
8	4.5	0.085
9	6.0	0.11
10	9.0	0.16
11	15.0	0.25
12	None	0.01

TABLE II.—AVERAGE ANALYSES OF 12 SHEETS OF EACH LOT OF LOW-SULFUR STEEL.

Ingot No.	Carbon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Copper, per cent.		
					Min.	Max.	Average.
2	0.06	0.42	0.048	0.030	0.012	0.012	0.012
3	0.05	0.44	0.058	0.032	0.020	0.024	0.021
4	0.06	0.43	0.057	0.032	0.032	0.036	0.034
5	0.05	0.44	0.058	0.035	0.044	0.052	0.045
6	0.06	0.44	0.056	0.033	0.048	0.052	0.050
7	0.05	0.43	0.048	0.026	0.064	0.080	0.071
8	0.06	0.43	0.056	0.032	0.088	0.100	0.096
9	0.06	0.42	0.048	0.028	0.112	0.120	0.116
10	0.06	0.43	0.050	0.026	0.156	0.172	0.165
11	0.05	0.43	0.051	0.028	0.248	0.264	0.254
12	0.06	0.43	0.056	0.031	0.012	0.016	0.014

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[1] E. A. and L. T. Richardson, "Observations upon the Atmospheric Corrosion of Commercial Sheet Iron," *Proceedings*, Am. Electro-Chemical Society, 1916.

[2] Kalmus and Blake, "Corrosion of Ingot Iron Containing Cobalt, Nickel or Copper," *Proceedings*, Am. Inst. Chem. Engrs., 1917.

addition of small percentages of copper, nickel and cobalt (from 0.25 to 3.0 per cent) to American ingot iron, are more resistant to atmospheric corrosion than the pure American ingot iron from which the alloys were prepared."

TESTS OF LOW-SULFUR COPPER-BEARING STEELS.

Following the work done by Buck and Handy, which suggested that the influence of copper in steel in retarding corrosion is noticeable at much lower copper contents than have previously been given any consideration, the writer undertook a series of service tests to determine the effect of copper in the very low ranges of percentages. Unfortunately for the purposes of these tests, all steel contains at least a slight trace (approximately 0.01 per cent) of copper and we were unable to obtain material entirely free from this element.

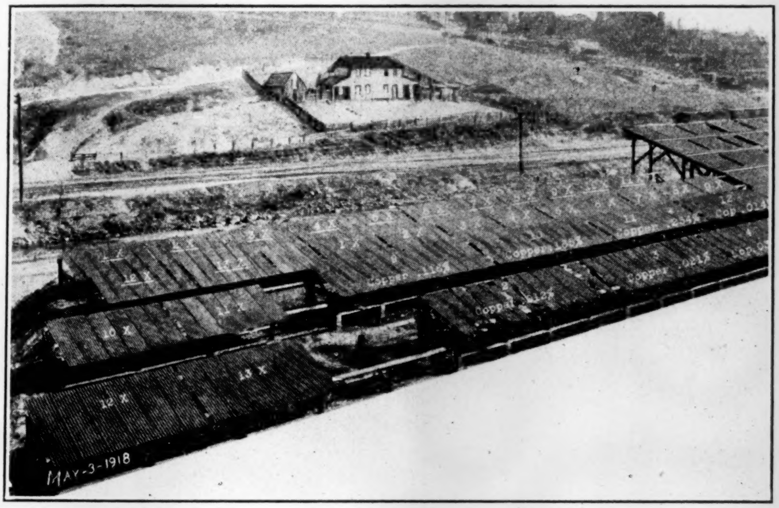

FIG. 1.—"X," High-Sulfur Sheets Exposed 2 Months; Others Low-Sulfur Sheets Exposed 1 Year. Underlined Numbers are No. 16 Gage; All Others No. 26.

A normal basic open-hearth heat was tapped and additions of copper made to the ingots during pouring, as indicated in Table I.

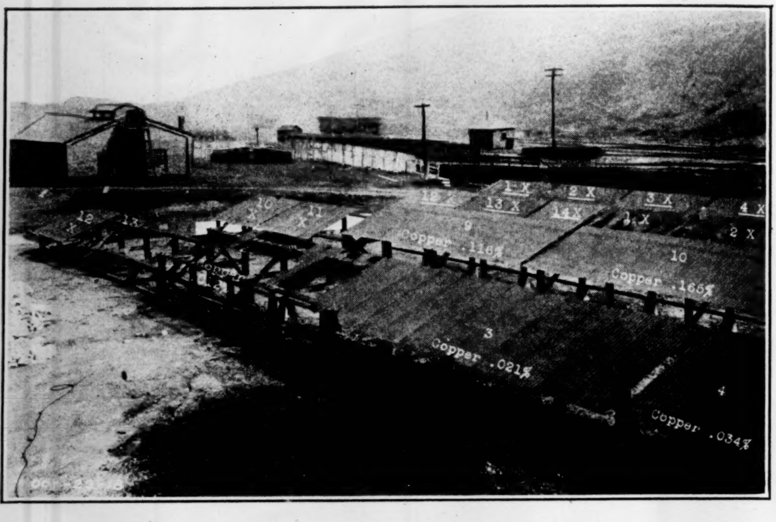
1 X
2 X
3 X
4 X
12 X
13 X
14 X
9
Copper .116%
10
Copper .166%
3
Copper .021%
4
Copper .034%

FIG. 2.—"X," High-Sulfur Sheets Exposed 7½ Months; Others Low-Sulfur Sheets Exposed 17 Months. Underlined Numbers are No. 16 Gage; All Others No. 26.

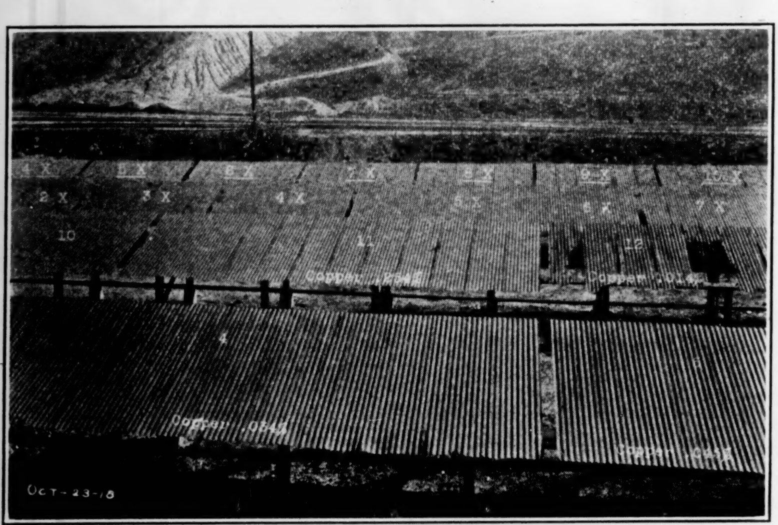
2 X
3 X
4 X
10
11
12
4
Copper .034%
Oct-23-18

FIG. 3.—"X," High-Sulfur Sheets Exposed 7½ Months; Others Low-Sulfur Sheets Exposed 17 Months. Underlined Numbers are No. 16 Gage; All Others No. 26.

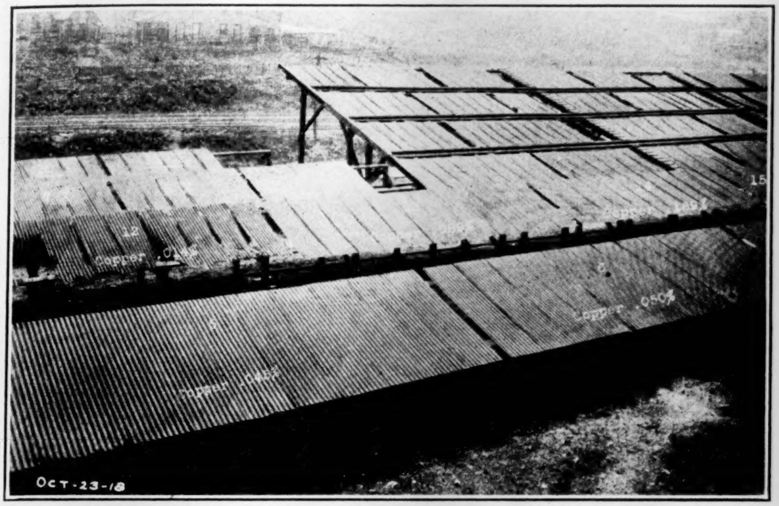
15
12
Copper .014%
Copper
8
Copper .050%
5
Copper .046%
OCT-23-18

FIG. 4.—"X," High-Sulfur Sheets Exposed 7½ Months; Others Low-Sulfur Sheets Exposed 17 Months. Underlined Numbers are No. 16 Gage; All Others No. 26.

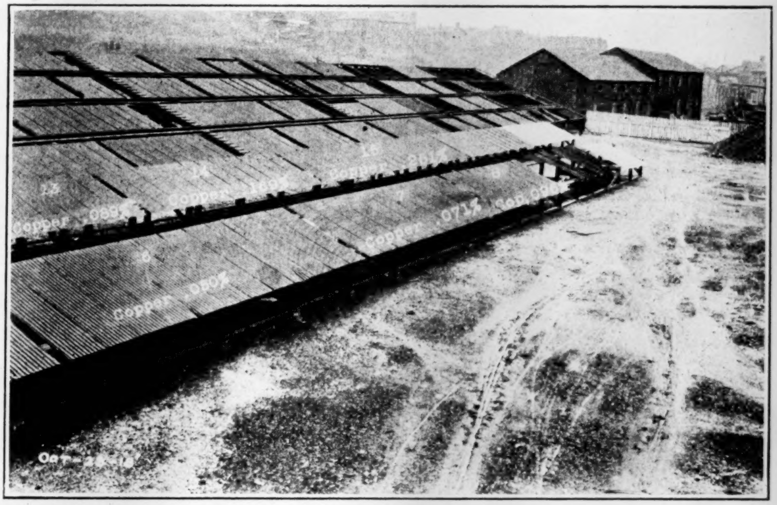
13
14
15
Copper .089%
Copper .169%
Copper .201%
7
Copper .071%
8
Copper .050%
OCT-23-18

FIG. 5.—No. 26 Gage, Low-Sulfur Sheets Exposed 17 Months.

All of these ingots were then put through the usual operations of reheating, blooming, and bar-rolling, and a number of bars taken from each, representative of the full length of the ingots from top to bottom. These bars were then rolled into sheets and all annealed at the same time in the same annealing box. Twelve sheets of each grade were then taken at random, a 2-in. strip cut lengthwise from the side of each, and the sheets (now No. 26 gage, 26 by 96-in.) were corrugated ready for exposure. The 2 by 96-in. strips mentioned above were sent to the laboratory, where 2 by 4-in. pieces were cut from each (after discarding 24-in. from the ends of the strips) for analysis and weight tests which will be described later. The average analytical results are given in Table II, the minimum, maximum and average results for copper being included. That the copper was uniformly diffused throughout the ingots is evidenced by these results.

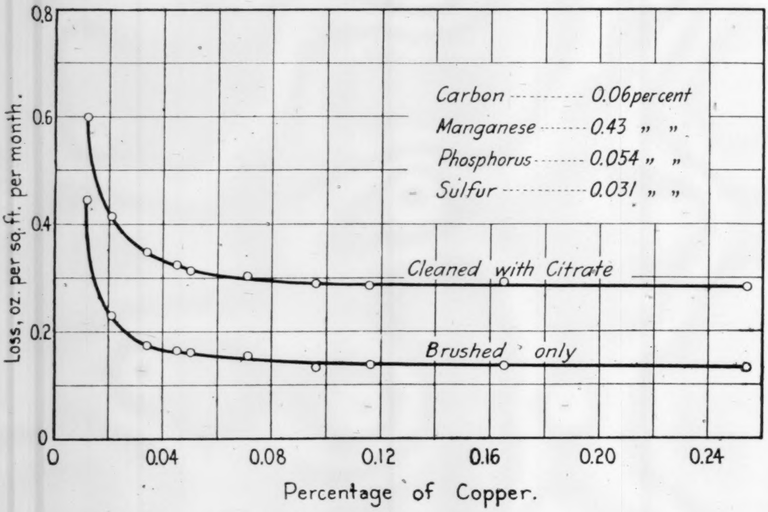

FIG. 6.—Losses in Weight of 2 by 4-in. Test Pieces from Low-Sulfur Steel. See Table III.

The full sized, unprotected corrugated sheets were placed on racks on May 11, 1917, in numerical order, both as to grades and also as to individual sheets of each grade, in the Connellsville Coke Regions of Pennsylvania. Fig. 1 shows the condition of panels Nos. 2, 3, 4, 9, 10, 11, and 12 after one year's exposure, and Figs. 2, 3, 4, and 5[1] show the condition of all of the panels after a little more than 17 months' exposure. The influence of as low an amount as 0.021 per cent of copper is quite apparent, while the advantage increases as the copper content rises.

The 2 by 4-in. test pieces cut from these sheets were carefully weighed, after removing all mill scale, and exposed in racks at the same time and place as were the large sheets. At the end of 5½ months, one-third (4 pieces) of each lot were removed from the test, another third at the end of 9½ months, and the remainder at the end of 18 months. These test pieces were all given exactly the same treatment by loosening the rust film and brushing with a wire brush. The treatment removed the major part of the rust, leaving approximately the same amount on each piece, and the losses in weight by this method of cleaning give a fair comparison. However, to obviate possible weight differences in thickness of the rust

TABLE III.—LOSSES IN WEIGHT OF 2 BY 4-IN. TEST PIECES FROM LOW-SULFUR STEEL.

Ingot No.	Copper, per cent.	Average Losses of 12 Pieces of Each Lot, oz. per sq. ft. per month.	
		Brushed Only.	Cleaned with Citrate.
2	0.012	0.445	0.599
3	0.021	0.230	0.415
4	0.034	0.176	0.349
5	0.045	0.165	0.324
6	0.050	0.161	0.318
7	0.071	0.155	0.302
8	0.096	0.136	0.290
9	0.116	0.138	0.287
10	0.165	0.134	0.291
11	0.254	0.131	0.281
12	0.014	0.370	0.533

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[1] Panels Nos. 13, 14 and 15 are from last three ingots of low-sulfur heat, to which varying amounts of boron-copper were added. The results were the same as with similar amounts of pure copper.

film left on the test pieces, they were, after weighing, again cleaned in an ammoniacal solution of ammonium citrate, which completely removes the remaining rust with but slight and quite uniform iron loss.

Table III gives the average loss in ounces per square foot of sheet per month for each lot of steel, and Fig. 6 gives the same information in graphic form.

It will be noted that the maximum effect is at about 0.08 to 0.09 per cent of copper, where the curve becomes approximately parallel to the abscissa, and that the influence of the lower amounts is progressive.

TABLE IV.—AVERAGE ANALYSES OF 12 SHEETS OF EACH LOT OF HIGH-SULFUR STEEL.

Ingot No.	Carbon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Copper, per cent.		
					Min.	Max.	Average.
1-X..........	0.09	0.43	0.110	0.053	0.006	0.008	0.008
2-X..........	0.09	0.42	0.115	0.055	0.016	0.018	0.017
3-X..........	0.10	0.43	0.116	0.057	0.024	0.028	0.026
4-X..........	0.09	0.42	0.109	0.051	0.032	0.040	0.036
5-X..........	0.09	0.43	0.112	0.053	0.044	0.048	0.045
6-X..........	0.09	0.43	0.110	0.053	0.052	0.056	0.054
7-X..........	0.10	0.42	0.110	0.054	0.080	0.084	0.081
8-X..........	0.10	0.42	0.123	0.055	0.108	0.112	0.109
9-X..........	0.09	0.40	0.106	0.055	0.124	0.132	0.129
10-X..........	0.10	0.42	0.110	0.055	0.156	0.160	0.159
11-X..........	0.09	0.42	0.111	0.055	0.196	0.204	0.201
12-X..........	0.09	0.42	0.112	0.056	0.246	0.250	0.249
13-X..........	0.10	0.40	0.115	0.055	0.008	0.012	0.010

TESTS OF HIGH-SULFUR COPPER-BEARING STEELS.

Previous work by the author has shown that sulfur is detrimental to steel from a corrosion standpoint, and that the beneficial effect of copper is probably due to its control of the sulfur. In order to obtain further information on this subject, and to procure additional data concerning the copper-sulfur equilibrium, we decided to duplicate the experiments

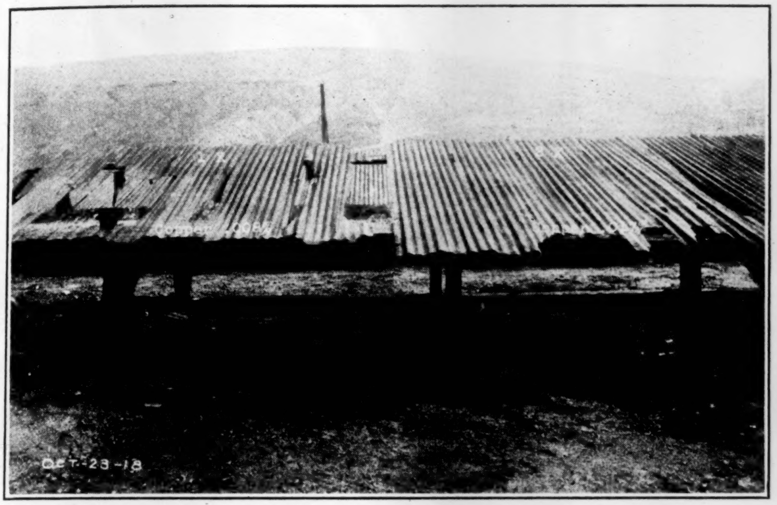
Copper .008%
OCT-23-18

FIG. 7.—No. 26 Gage, High-Sulfur Sheets Exposed 7½ Months.

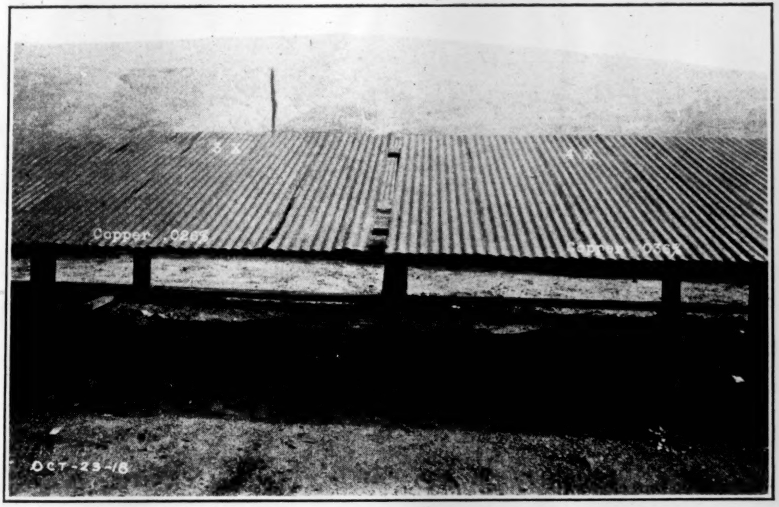
3 %
4 %
Copper .026%
Copper .036%
OCT-23-18

FIG. 8.—No. 26 Gage, High-Sulfur Sheets Exposed 7½ Months.

thus far described, with another basic open-hearth heat carrying higher sulfur.

Table IV gives the average analyses of 12 sheets of each lot from this heat. The difference in phosphorus content is not important, since it is generally conceded that higher phosphorus, from a corrosion standpoint, is rather beneficial than harmful. Six sheets of each of these lots, No. 26 gage, as well as six sheets of No. 16 gage from the same ingots, were exposed at the same place as the former tests, on March 11, 1918. The letter "X" has been added to the panel numbers to distinguish this heat from the low-sulfur heat discussed earlier in this paper, and the No. 16 gage panels are distinguished by having the numbers underlined. Fig. 1 shows these sheets shortly after exposure, and Figs. 2, 3, 4, 7, 8, and 9 show the condition of the various panels on October 23, 1918, after about 7½ months' exposure.

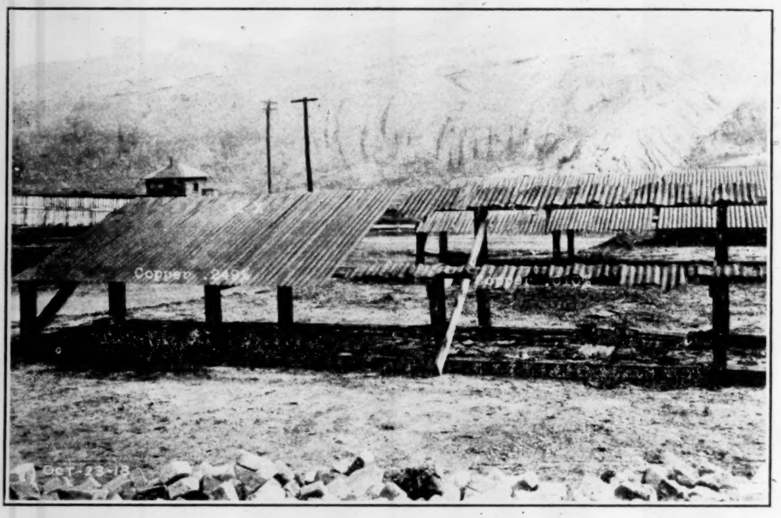

FIG. 9.—No. 26 Gage, High-Sulfur Sheets Exposed 7½ Months.

Table V gives the average loss in ounces per square foot of sheet per month for the 2 by 4-in. test pieces from the high-sulfur heat, both brushed and cleaned with ammonium citrate. Fig. 10 gives the same information expressed graphically.

It will be noted that the corrosion losses in the high-sulfur heat have been very much greater in the low-copper ranges than was the case with the heat containing lower sulfur, and that the approximate maximum effect is not attained until a copper content of about 0.10 per cent is reached. There is also a slightly greater loss in the high-sulfur heat even in the higher copper ranges, but this is no doubt explained by the fact that the corrosion rate of copper steels diminishes rapidly, as the time of exposure increases, due to the protective action of the dense rust film formed during the early months of exposure. This protective action of the rust film on copper steels was also mentioned by Kalmus and Blake.

TABLE V.—LOSSES IN WEIGHT OF 2 BY 4-IN. TEST PIECES FROM HIGH-SULFUR STEEL.

Ingot No.	Copper, per cent.	Average Losses of 12 Pieces of Each Lot, oz. per sq. ft. per month.	
		Brushed Only.	Cleaned with Citrate.
1-X	0.008	1.456	1.644
2-X	0.017	1.155	1.395
3-X	0.026	0.805	1.094
4-X	0.036	0.615	0.888
5-X	0.045	0.467	0.745
6-X	0.054	0.361	0.625
7-X	0.081	0.260	0.521
8-X	0.109	0.231	0.488
9-X	0.129	0.220	0.479
10-X	0.159	0.213	0.460
11-X	0.201	0.200	0.445
12-X	0.249	0.196	0.440
13-X	0.010	1.251	1.516

It was impossible to expose the test pieces of the second heat as long as was the case with the first heat, inasmuch as the very low copper steels totally disappeared, due to the higher sulfur, in about 7 months as compared with more than 18 months with the low-sulfur steel. Due to this difference in time factor, the comparative results are somewhat affected in favor of the latter heat. However, the author has under exposure a set of No. 16 gage test pieces from this second heat, which, together with the ultimate length of life of the full size sheets, should give more nearly comparative results.

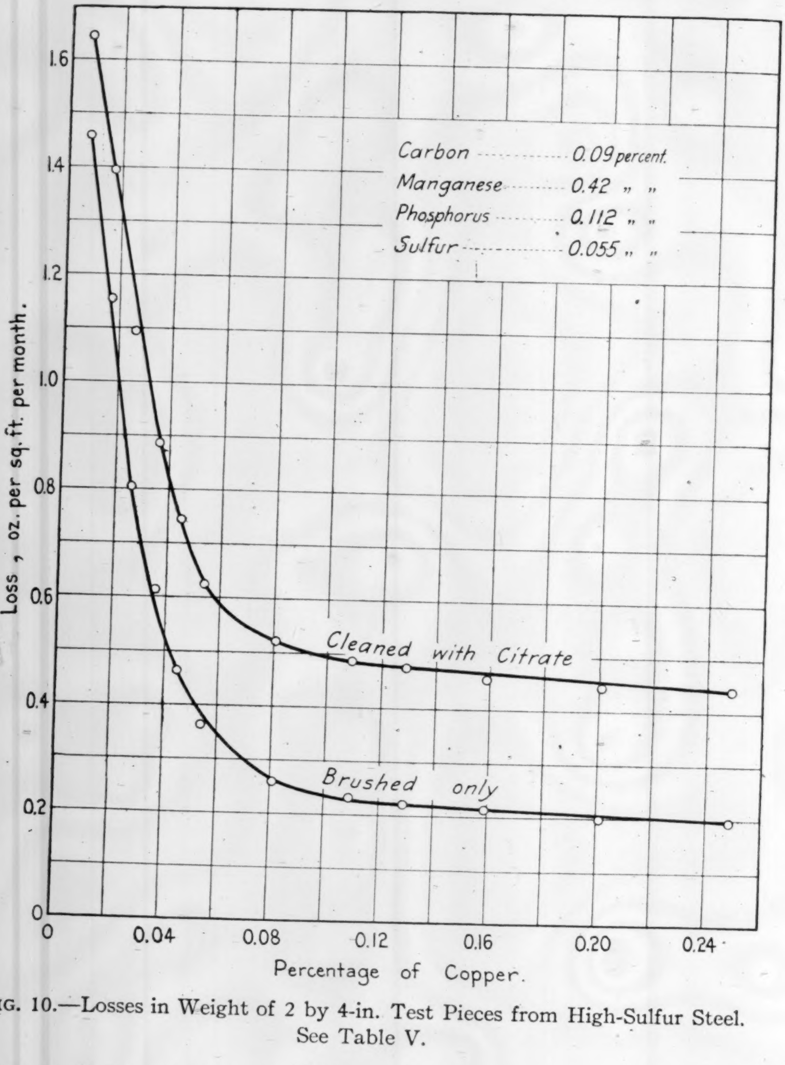

FIG. 10.—Losses in Weight of 2 by 4-in. Test Pieces from High-Sulfur Steel. See Table V.

The tables and curves submitted herewith give a very clear idea of the influence, in retarding the corrosion of steel, of as low a copper content as 0.02 and 0.03 per cent. The influence of sulfur in accelerating the corrosion rate is also quite apparent, and we obtain some further information relative to the combined effects of sulfur and copper, and the amounts to which it is necessary to alloy copper with steel to obtain practical results. Additional research is being conducted to determine the time factor and magnitude of the protective effect of the rust film on copper steels as compared with normal steels.

CONCLUSIONS.

1. Very low amounts of copper in steel materially lower the corrosion rate.

2. Steel with 0.03 per cent of copper corrodes only 60 to 70 per cent as fast as the same steel with 0.01 per cent of copper.

3. It has been customary to consider a copper content of any amount under 0.05 per cent as a trace, and it may be desirable to reinterpret many corrosion data obtained in work in which the effect of these minute amounts of copper has not been taken into account.

4. In order to leave an ample factor of safety, steel to resist atmospheric corrosion should contain not less than 0.15 per cent of copper.

5. Copper in amount of 0.12 per cent is sufficient to neutralize the influence of sulfur as high as 0.055 per cent (two sheets of lot 9-X contained 0.074 per cent of sulfur, and the losses on these were slightly lower than the average for that lot).

6. Copper in amount of 0.15 per cent is sufficient to protect steels even if the sulfur content is considerably higher than normal.

DISCUSSION.

Mr. Robinson. MR. A. F. ROBINSON (*by letter*).—I have read the paper by Mr. Buck with considerable interest.

A year or two ago, I visited the Tin Plate Company's mill at Gary, Indiana, several times to look at similar tests which were being carried out on No. 26 gage corrugated sheets. The racks and method of exposure were almost identical with those shown in Mr. Buck's paper. The conclusions I drew from witnessing these tests at Gary were:

1. Percentage of copper from 0.15 to 0.25 per cent does retard the rusting of steel.
2. All soft steels, both with and without copper, will rust after exposure to the atmosphere.
3. There is no such thing as absolutely rustless iron or rustless steel. While the rusting may be relatively slow it still exists, and our only final recourse is in the protection covering put on the sheets.
4. To put the matter bluntly, I do not believe it is worth very much extra expenditure to obtain chemically pure iron or copper-bearing steel when our sole protection from rust is due to the galvanizing, the paint coating or other method of treatment for protection.

I am calling attention to this feature, as it seems to me the paper in question leaves the impression that the copper-bearing steels are valuable as rust preventers.

Mr. Cushman. MR. A. S. CUSHMAN (*presented in written form*).—Without desiring to interject anything of a controversial nature into this discussion, I cannot refrain from expressing my opinions in regard to the reasons why a small copper content in iron and steel has a restraining action on corrosion when the attack is of an acid nature. Mr. Buck's theory is that the copper reacts with the sulfur in some way and that 0.15 per cent of copper in steel will neutralize the deleterious effect of abnormally high sulfur. I have as yet seen no evidence that would support this theory, and I cannot help feeling that it is a dangerous metal-

Mr. Cushman.

lurgical practice to permit the existence in steel of higher sulfur content, trusting to the neutralizing or physicing action of a modicum of copper. As a matter of fact, a copper content will confer acid resistance to very pure iron in which the sulfur is reduced practically to traces, so that in this case at least the resistance is not imparted by any interaction between copper and sulfur. The question of the effect of copper under non-acid conditions still requires systematic investigation by Committee A-5 on Corrosion of Iron and Steel. In my own investigations, any beneficial effect of copper is confined to decidedly acid environment and media. In cases in which the conditions is neutral, the copper seems to be inert, while under alkaline conditions, as might be expected, the results are the reverse of those obtained under acid conditions. F. N. Speller has found that on the inside of pipes carrying water, the copper steel was not more resistant to corrosion than ordinary steel.

My own explanation of the restraining of copper against attack by an acid medium is quite different from Mr. Buck's. It is well known that copper will plate out of an acid solution on to steel with which the solution may be in contact. If the rain water, say in Pittsburgh, contained a small fractional percentage of copper sulfate, copper would immediately plate out on a newly exposed test sheet on which it fell. Actually, however, the copper is dissolved in the steel and it is sulfuric acid which concentrates upon the surface, exerting a solvent action. The copper now is continually tending to plate back, and thus exhibits a restraining action on the solution pressure of the iron ions. I do not mean to convey the impression that copper passes into solution as sulfate, only to turn right around and plate out again; but I conceive the action that takes place as something akin to, if not directly linked up with, the phenomenon which electrochemists term over-voltage. Over-voltage simply means that value of electrochemical potential set up by hydrogen while being liberated on a cathode, which is in excess of the value hydrogen ought to give. In simple language, before iron can turn into rust it must go into solution, and hydrogen must be liberated. Any condition that tends to hold back the liberation of hydrogen acts as a restrainer of corrosion, but only under the given condition under which it can so act. If we paint

Mr. Cushman. the surface of steel, or coat it with another metal, the conditions are immediately quite different, and an entirely new set of electrochemical equilibria are introduced.

This restraining action of copper takes place whether the steel containing it is immersed in dilute sulfuric acid in a beaker, or whether it is filmed over with sulfuric acid out of doors, but there is this difference: in the former case there is a minimum of oxygen present, while in the latter an inexhaustible quantity of oxygen is supplied by the atmosphere. In both cases hydrogen is liberated, but in the first case ferrous sulfate passes into solution, while in the second the ferrous sulfate is immediately oxidized or, better, hydrolyzed, and hydrated iron oxide or iron rust is formed. Electrochemists have frequently called attention to the fact that freshly formed iron rust is electro-negative to the underlying base metal, and it is believed by some investigators that this fact leads to accelerated progressive corrosion. This idea is sometimes expressed in the phrase: Rust breeds rust. Now, there can be no doubt, as Mr. Buck claims, that alloying so electro-negative a metal as copper with steel renders the steel more electro-negative in character, which is a point in its favor when the corrosive attack is of a decided acid nature, but which may, and I believe will, prove to be a disadvantage under all other conditions.

The very fact that copper confers resistance to acid attack makes a ferrous metal carrying 0.20 per cent or over difficult to pickle in preparation for galvanizing, and since a very considerable quantity of all sheet metal manufactured is zinc coated, I am led to anticipate that on account of this economic factor the tendency will be to run to lower rather than higher copper content. There will also probably be a tendency toward higher sulfur in sheet steel, as a result of Mr. Buck's interpretation of his latest weather exposure tests from which he concludes that 0.12 per cent copper is sufficient to neutralize the bad effect of 0.055 per cent of sulfur. Mr. Buck's statement that steel with 0.03 per cent copper corrodes only 60 to 70 per cent as fast as the same steel with 0.01 per cent copper under acid atmospheric conditions is, however, reassuring if it can be confirmed, for the reason that it is becoming increasingly difficult to make open-hearth steel with a copper content less than 0.03 per cent.

Mr. Cushman. I have collected considerable data in the last two years bearing on the corrosion under varying conditions of sheet metal carrying protective coatings of all sorts, but as the material is not germane to the present discussion, I reserve it for presentation at another time.

Mr. Lasier. MR. E. L. LASIER (*presented in written form*).—I am mainly interested at this time in Mr. Buck's paper on the effect of copper content in steel in resisting corrosion, because of the conditions attending any attempt to investigate that subject along scientific and technologic lines.

Mr. Buck has presented the subject as involving tests principally, if not solely, on sheet metal. Briefly, the net deduction from the paper is that, based on the curves shown therein, the "turning points," so to speak, in sheet steel of the compositions given, in so far as the relation to corrosion is concerned, are about 0.10 per cent copper for the so-called "low-sulfur" steel and 0.11 per cent for the so-called "high sulfur" steel. In his conclusion the author increases these values to 0.15 per cent "in order to leave an ample factor of safety." As a conclusion, without any restriction to steel sheets similar in nature and composition to those investigated, based on Mr. Buck's own statements it may be inferred that a copper content of 0.15 per cent *per se* will insure that a steel of any form, condition, composition or treatment will "resist atmospheric corrosion," whatever that indefinite expression may mean.

The conclusion reached may or may not be true. I hope it is true; but I certainly believe that with the data presented by Mr. Buck and even with the other data heretofore reported by other investigators on the subject, the broad and general conclusion given is not warranted.

Moreover, besides the question of the influence of copper content in resisting corrosion, there is involved the additional question: What effect do varying copper contents have on the other properties of steel, namely, the physical, mechanical, thermal, weldability properties, etc.? That question is especially important in connection with steels intended for purposes where strength is essential.

In order to develop the subject, may I ask Mr. Buck two questions, which appear to me to be important and to some measure controlling:

Mr. Lasier. 1. What test data are available or deductions possible, upon the relation of copper to the several other elements which may be present in steel in varying amounts?

2. In structural steel, what reliable data are available to show the effect of copper content on properties other than resistance to corrosion?

Much has heretofore been presented on the subject at issue. For years the theory has been advanced that copper in small amounts is beneficial to steel, especially in its resistance to corrosion, and that therefore copper steels are superior to ingot iron, wrought iron and boron-copper steel, etc., in that respect. The subject is not simple, however, and conflicting statements or mitigating circumstances have been just as frequently reported.

I have in mind, for instance, some tests made several years ago on some copper-bearing steel sheets, and in particular three sheets involved which for convenience will be referred to as Nos. 1, 2 and 3. All three were of similar composition except as to phosphorus, and all three had small and similar amounts (which I do not recall) of copper. After identical atmospheric exposure, No. 1 was in far better condition than No. 2, and the engineer in charge of the tests explained the result by the fact that No. 1 had a phosphorus content exceeding that of No. 2; sheet No. 3, however, had about twice the phosphorus content of No. 1 and yet sheet No. 3 was in the poorest condition of the three. This and other facts justify the inference that the combination of elements present must be considered in passing on the effect of copper content; especially is this question important when the alloy steels are involved.

Again, assuming that a copper content makes a steel more resistant to corrosion, is that property obtained at the expense of other properties desirable especially for structural steels? Clevenger and Ray[1] have presented this subject at some length and in that connection have reviewed the previous work of others in the same field. Hayward and Johnston[2], Storey[3] and others have also and more recently submitted data upon the

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[1] Clevenger and Ray, "The Influence of Copper upon the Physical Properties of Steel," *Bulletin No. 82*, Am. Inst. Min. Engrs., pp. 2437–2475 (October, 1913).

[2] Hayward and Johnston, "The Effect of the Presence of a Small Amount of Copper in Medium Carbon Steel," *Bulletin No. 133*, Am. Inst. Min. Engrs., pp. 159–167 (January, 1918).

[3] *Transactions*, Am. Electrochemical Soc., Vol. XXXII, pp. 285–316 (1917).

Mr. Lasier.

subject. While the results reported have been in many particulars very conflicting, in general they lean toward the inference that the addition of small amounts of copper raises slightly the yield point and tensile strength of steel, at the expense, however, of ductility. In general the past experimental work reported tends to establish the inference that copper, as an addition to steel, exerts an influence similar to that of nickel. Many properties, however, such as, for illustration, the ability of steels to be forged or welded, may very possibly be adversely affected when copper is present. Some references have been found to the effect that small percentages of copper tend to promote segregation; other references report exactly the contrary. It is very probably true that copper content tends to eliminate sulfur, and therefore tends to make the steel resist corrosion to a greater extent than if absent; the effect is so intervolved, however, with the effect of other constituents, elements and conditions, that it is difficult to arrive at a definite and exact conclusion.

Then, too, it must be recalled that the work of some investigators whose efforts merit consideration, such as that of A. S. Cushman,[1] indicate as the result of many tests that copper is not beneficial to iron in aiding it to resist corrosion, but on the contrary is in many cases deleterious.

I do not desire to be misinterpreted as being opposed to the idea that small percentages of copper in steel are beneficial. Personally I think that, based on the mass of data available, a general conclusion is justified that low copper content in steel exerts *some* influence in retarding corrosion; the question is, however, whether a quantitative conclusion can be drawn or prediction of performance made, except under very restricted conditions, involving the specific composition, condition or form and previous treatment of any particular steel, the use to which that steel will be subjected and the corroding media which will be encountered. There is therefore need for caution in interpreting results or drawing conclusions or inferences. So much has been said and reported for many years on the influence of copper that I merely am desirous as a Materials Engineer of

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[1] A. S. Cushman, *Bulletin No. 84*, Am. Inst. Min. Engrs., pp. 2936–2938 (December, 1913).

Mr. Lasier. getting at the real truth of the matter and ascertaining whether or not copper, *in itself*, is a panacea for steel corrosion ills.

Mr. Buck. MR. D. M. BUCK.—The corrosion test which Mr. Robinson saw at Gary, Indiana, was a duplicate of similar tests made at Scottdale, Pa., Atlantic City, N. J., etc., which were reported in papers for the American Chemical Society in 1913 and the American Iron and Steel Institute in 1916.

The Gary test was made to compare the corrosive effect of the atmosphere near an inland lake with the atmospheres of the Pennsylvania Coke Regions and the Atlantic Sea Coast. The relative order of failure of the sheets at Gary, Indiana, was the same as in the other localities, and the time of failure was about the same as in the coke region test.

I am quite in accord with Mr. Robinson's conclusions as stated in items 1 and 2 of his discussion, as well as the first sentence of item 3. I take exception, however, to statements made by Mr. Robinson in item 4. It is certainly true that, from a corrosion standpoint, it makes no difference what the character of the base metal may be so long as the protective coating, whatever it may be, is intact, unbroken and impervious. We know, however, that protective coatings are not perfect, and when the base metal becomes exposed through mechanical damage or breaking down of the protective film, it becomes a matter of considerable moment whether or not the base metal possesses the quality of rust resistance.

It is also true that considerable steel and iron material is exposed either without any protective coating or with a coating which is quickly destroyed. The steel freight car is a prominent example of the latter class.

Mr. Robinson states that my paper leaves the impression that copper-bearing steels are valuable as rust preventers. I believe a careful reading of the paper will show that I have not claimed that rusting is *prevented* by the use of copper steel, but that the corrosion rate is *considerably lowered* under atmospheric conditions.

(*Author's Closure by letter*).—Mr. Cushman in his discussion of my paper lays particular stress upon the restraining action of a small copper content in iron and steel *when the attack is of an acid nature.* The tests reported upon in my paper were conducted at Scottdale, Pa., on the edge of the Connellsville Coke

Mr. Buck.

Regions; and although the atmosphere at this place formerly carried a considerable amount of fumes from the coke ovens, yet several years ago all of the ovens in the immediate vicinity of the tests were abandoned, and at the present time there are no operating ovens within several miles. The air, therefore, is fairly typical of an ordinary industrial district. It is quite true that such air contains a small amount of sulfurous gases from burning fuel, and may therefore be considered of an acid nature. It is equally true that there are practically no districts where the air does not carry acid gases to a greater or less extent, so that the difference may be considered as one of degree and not of kind.

I have conducted service tests in several different characters of atmosphere, and it has been my invariable experience that while failures occurred at a considerable later date in the purer airs, when comparing copper steels with other materials the same order of failure occurred in the pure air as in a district where the air is less pure.

Mr. Cushman is rather unfair in his inference that the steel makers will exercise less care in the control of the sulfur content of steel. By the introduction of copper we can control the deleterious effect of fairly high sulfur from a corrosion standpoint. We have given this information only as a matter of scientific interest, and do not advocate any diminution of the customary care in reducing steels to as low sulfur as is possible under the best practice.

Mr. Cushman states that if the surface of steel is painted or coated with another metal, "the conditions are immediately quite different, and an entirely new set of electrochemical equilibria are introduced." In addition to the tests which I have made on uncoated sheets, I have also conducted several series of tests on coated sheets, and I have found approximately the same superiority for copper steels over those products under these conditions. No differences, of course, are noticeable so long as the protective coating remains intact, but when the coating becomes removed for any reason, the greater rust resistance of copper steels becomes evident; and I have seen no indications of electrochemical effects between the coating and the base metal in copper steel in any way different from those ordinarily present with normal steel.

Referring to Mr. Lasier's discussion of my paper, I accept

Mr. Buck. as just his criticism that the wording of the conclusions should be modified to include only mild steels. The beneficial influence of copper in retarding the corrosion of mild steel under atmospheric conditions is, however, not confined to any such narrow limits as Mr. Lasier fears. The author observed his own tests and those conclusions by other investigators which cover practically the whole field of mild open-hearth and Bessemer steels of widely varying chemical composition so far as the usual metalloids are concerned. I have also experimented under different conditions of heat treatment, from unannealed sheets to product which has been annealed at a temperature considerably higher than normal, and with varying amounts of cold work. Under all of these conditions, 0.25 per cent copper or even less has a very marked influence in lowering the corrosion rate. Nor is this tendency confined to sheet sections, since careful work on wires and tubes under atmospheric conditions gives results similar to those on sheets.

Referring to Mr. Lasier's two questions, I am not able to furnish data concerning sheets other than mild open-hearth and Bessemer steels with a rather wide variation in chemical analysis and physical treatment. Our experience with such steels shows that the physical properties as manifested by the tension test are changed only to a very slight extent by a copper content of 0.25 per cent or under, and such slight changes are not, as Mr. Lasier suggests, at the expense of ductility, but quite the opposite. Perhaps Mr. Lasier's questions may be answered in a practical way, at least so far as sheet metal is concerned, by stating that during the past eight or nine years we have furnished to the trade more than one million tons of copper steel sheets and plates, which have been put to a very wide variety of uses without causing adverse comment from the standpoint of physical properties. Nor have we found that the weldability is affected by a copper content of 0.25 per cent, although it is quite probable that if the copper content is raised to 1 per cent or higher the welding properties are considerably impaired.

Copper does not promote segregation, nor have I been able to check the results of Clevenger and Ray, who found a slight tendency toward removal of sulfur by the introduction of copper. Copper in my opinion controls the harmful effects of sulfur without its actual removal.

SOME PHYSICAL CONSTANTS OF AMERICAN MALLEABLE CAST IRON.

By H. A. Schwartz.

SUMMARY.

Very little information of a quantitive character as to the physical constants of malleable cast iron is available in the literature. From time to time the National Malleable Castings Co. has had occasion to investigate most of the principal properties of this material. While the work involves no novel principles, it is thought that the data secured will be of value to engineers interested in the use of the product. In order to render the information available to such persons, the data obtained are summarized in the following paper.

The data and conclusions are to be understood as applying only to American "black heart" malleable and not to the European decarbonized product.

SOME PHYSICAL CONSTANTS OF AMERICAN MALLEABLE CAST IRON.

BY H. A. SCHWARTZ.

INTRODUCTION.

Malleable cast iron is made by producing castings containing all their carbon in the combined state, and then securing the complete conversion of the carbon into the free state by suitable heat treatment at a temperature considerably below the melting point. The material consists of a ferrite matrix through which the carbon is distributed in the temper or amorphous form. Its properties are therefore dependent upon the physical properties of the ferrite and upon the amount and geometric form of the included carbon. Consequently the physical constants of malleable cast iron will vary with the chemical composition and heat treatment of the material.

Only tensile strength has been investigated in very great detail in its relation to chemical composition. This work involved a critical study of the chemical and physical properties of many thousands of heats. The result of this investigation is of importance in the present connection only to the extent that it corroborates the conclusion that the amount and form of the free carbon present is the determining factor as regards to quality of the product. The requirements of satisfactory commercial practice are such as to confine the chemical composition within limits so narrow as to practically eliminate the chemical composition of the ferrite as a variable. The adoption of the A.S.T.M. Tentative Specifications for Malleable Castings[1] as a standard by the American Malleable Castings Association has further served to standardize the product.

The tests upon which this paper is based were made on material of such a character as to pass the present specifications satisfactorily, and may be understood as applying to a commercial product of that character. Furthermore they have all been made upon test specimens which are known to be free from defects such as shrinks or blowholes, but are not based upon material selected as being of superior quality. The results here given may therefore be considered as furnishing a conservative basis for engineering calculations.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part I, p. 464 (1918).

The reader, particularly if he be a resident of a foreign country, should bear clearly in mind the radical differences in principles and practice between the American and European industries. The aim of the latter is to produce a more or less completely decarbonized product containing no temper carbon. None of the statements in this paper are applicable to this "white heart" product.

MACHINING OF SAMPLES.

For the purpose of the writer's investigation it was usually necessary to provide test specimens of more accurate form than can be made by even the most careful molding practice. For example, it is well known that the determination of the elongation of a material is seriously interfered with by the presence of any surface defects in the test specimens, and such defects are practically certain to be present in an unfinished bar. Two courses were available: (1) to machine the test specimen after annealing, thereby introducing such an error as may result from the rejection of the surface metal; or (2) to grind the test specimen to size before annealing, thereby incurring a laborious and expensive method of preparation. Both means were used in preparing the specimens, dependent upon the individual circumstances.

BEHAVIOR UNDER TENSILE STRESSES.

The tensile properties of malleable cast iron are the only constants now defined by specification. The value assigned for tensile strength is now 45,000 lb. per sq. in., and the elongation required is $7\frac{1}{2}$ per cent in 2 in. From observation on tests covering many thousands of heats, the writer is of the opinion that the product made by reputable foundries to pass the A.S.T.M. specifications will actually average from 48,000 to 50,000 lb. per sq. in. in tensile strength, and will have an elongation in 2 in. of 10 to 15 per cent.

The stress-strain diagram shown in Fig. 1 is selected as typical, since it conforms in properties rather closely to the values assigned by this Society's specifications. It is plotted from extensometer readings on a test specimen 0.505 in. in diameter, 5 in. long between gage points, machined from a large casting. This test was made for the writer by Prof. Harold A. Thomas of the Rose Polytechnic Institute in September, 1918. This specimen is of interest in that it indicates the very satisfactory qualities that can be obtained on a test specimen machined from a large casting after annealing. The block from which this specimen was obtained was $4\frac{1}{2}$ by 9 by 14 in. when cast.

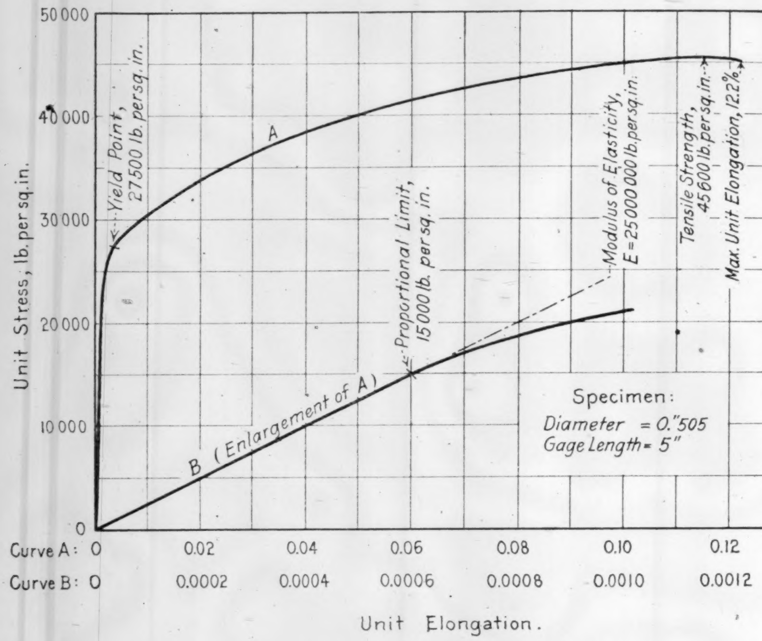

FIG. 1.—Stress-Strain Diagram of Malleable Cast Iron in Tension.

A sufficient number of tests in which the only variable is the machining of the specimen, whether before or after annealing, is not at hand to include satisfactory figures on this point. The reduction of area was not determined. A number of tests were made, however, on specimens ground to size before annealing. From these observations the following results are selected as typical:

TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT.	REDUCTION IN AREA, PER CENT.
55 200	19	18
55 100	13	20
55 200	17	23

The metal of which these specimens were made is considerably better than the requirements of the standard specification. Although closely alike in tensile strength, the three test specimens represent three different heats.

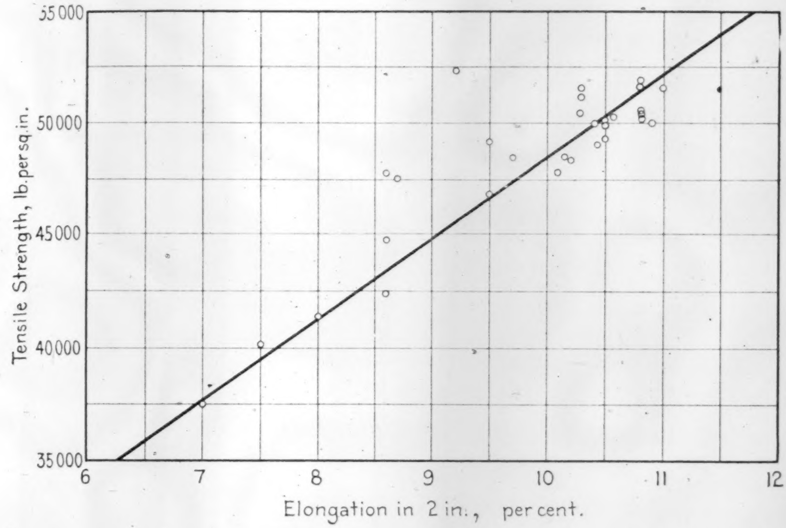

FIG. 2.—Relation Between Tensile Strength and Elongation of Malleable Cast Iron.

To record the fact that malleable cast iron differs from all other commercial iron alloys, in that its elongation increases with its tensile strength, Fig. 2 has been prepared. Each point on this graph indicates the tests of a group of heats of the same chemical composition, representing in all 840 heats. It will be seen that while the relationship between tensile strength and elongation is not absolutely quantitative, the general relationship that the two vary together is very clearly brought out.

BEHAVIOR UNDER COMPRESSIVE STRESSES.

From the nature of the material the ultimate strength in compression is rather vague, for actual failure may never occur, the material merely flowing out indefinitely with increase of load.

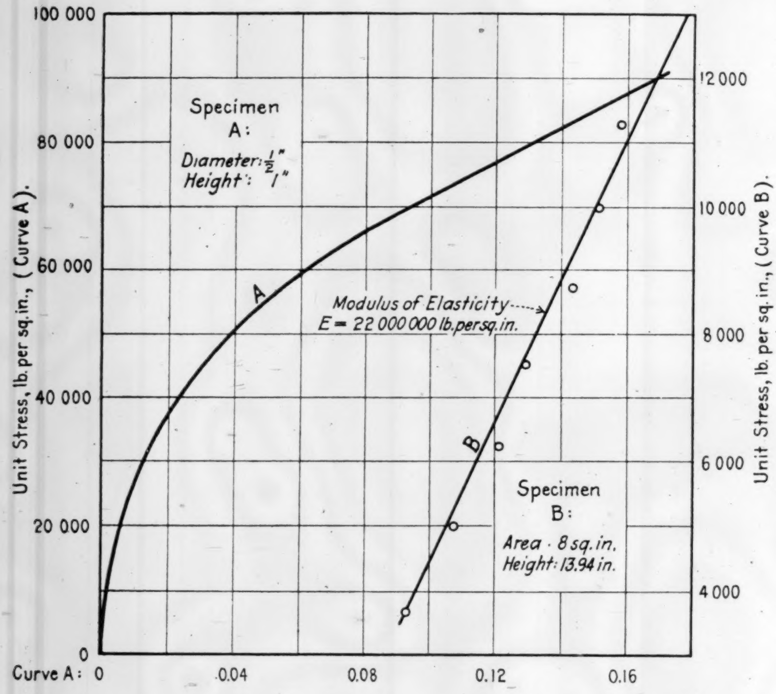

FIG. 3.—Stress-Strain Diagram of Malleable Cast Iron in Compression.

Fig. 3, curve *A*, indicates the stress-strain diagram as determined on a test specimen ½ in. in diameter and 1 in. high. It will be noted that the material has not actually failed, though it has been compressed to a point probably equivalent to the destruction of any actual structural detail. The tests were not sensitive enough definitely to determine the proportional limit, which, however, seems to be not far removed from 15,000 lb. per sq. in.

Curve *B* is a similar diagram made on a cylindrical specimen of the material whose tensile properties are plotted in Fig. 1, having a cross-sectional area of 8 sq. in., and a height of 13.94 in. The proportional limit has not been reached at the maximum load obtained in this test, 12,500 lb. per sq. in. The conclusion seems warranted that the elastic properties of the material in tension and in compression are approximately the same.

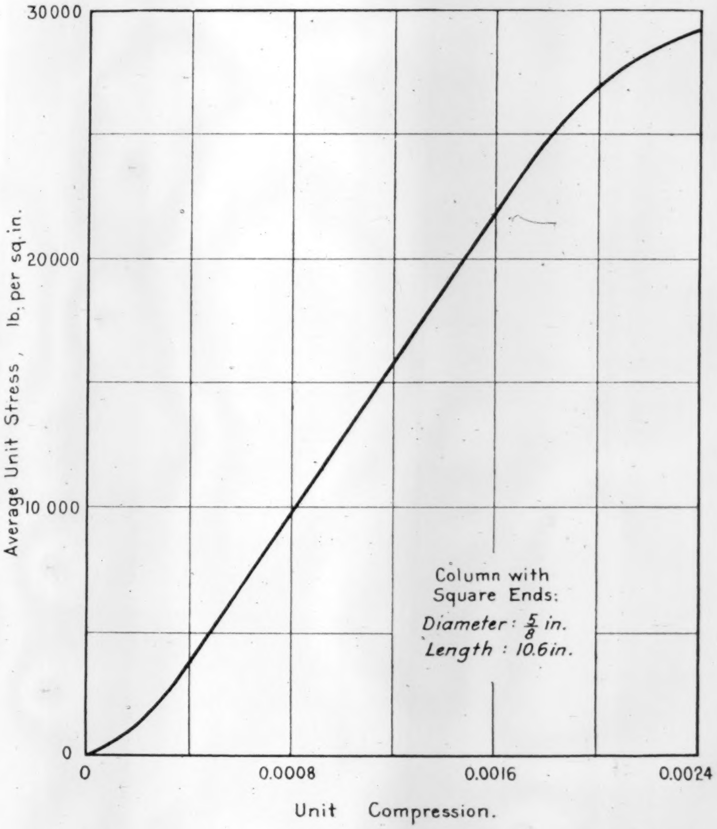

FIG. 4.—Stress-Strain Diagram of Malleable Cast Iron as a Strut.

BEHAVIOR OF MALLEABLE IRON AS A STRUT.

The data given under compression applied only to structural details in which the length is not large as compared with the diameter.

In order to give some idea as to the behavior of details in the form of columns made of malleable iron, a few tests were undertaken on specimens $\frac{5}{8}$ in. in diameter and 10.6 in. long, having ends of such a form as to cause the specimen to behave as a column with square ends.

In Fig. 4 is given a stress-strain diagram which is the average of tests on three different specimens of this character. Time has been lacking to make a sufficiently extended series of experiments to determine the application of Gordon's or similar formulas to malleable cast iron strut members.

BEHAVIOR UNDER CROSS-BENDING STRESSES.

Specifications R 17 of the United States Railway Administration, dated May 1, 1918, provide that the material in the form of bars 1 in. wide on supports 12 in. apart shall support certain specified loads at the center varying with the thickness of the bar but all corresponding fairly closely to the value 64,000 lb. per sq. in. for the modulus of rupture of the material.

It is the writer's observation that material passing the A.S.T.M. tensile test requirements invariably exceeds this requirement for modulus of rupture.

Fig. 5 is a stress-deflection diagram obtained on an unmachined specimen $\frac{1}{2}$ by 1 by 14 in. loaded at the center of a 12-in. span.

BEHAVIOR UNDER SHEARING STRESSES.

The data bearing on shearing stresses are based on a series of experiments conducted in cooperation with Professor Thomas at the Rose Polytechnic Institute in January, 1919. The tests were made both by punching a round hole 1 in. in diameter through plates approximately $\frac{1}{4}$ in. thick which had not been machined, and by subjecting round pins $\frac{7}{8}$ in. in diameter to double shearing. The pins were finished to size. Duplicate specimens were tested in order to compare the shearing stress in pins machined after annealing with the same constant determined on specimens ground to size before annealing.

Specimens for each of the three tests were at hand from the same metal. The average results of these tests were as follows:

SHEARING STRESSES, LB. PER SQ. IN.

BY PUNCHING.	BY SHEARING FINISHED PIN.	BY SHEARING PIN GROUND BEFORE ANNEALING.
45 152	40 340	41 350

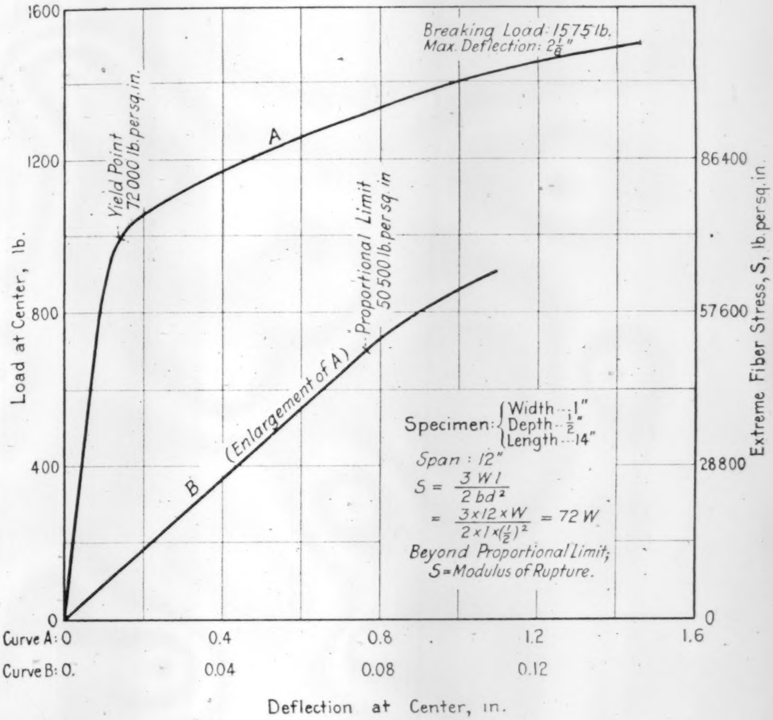

FIG. 5.—Stress-Deflection Diagram of Malleable Iron in Cross Bending.

The tests made by punching a thin plate indicate a higher shearing stress than that obtained by shearing pins. It seems quite certain that this is due to the fact that, in spite of every precaution, it is not possible to so accurately fit the specimen to the shearing block as to cause it to fail absolutely at the same time throughout its entire section.

BEHAVIOR UNDER TORSION STRESSES.

At the time the shearing experiments just described were made, two specimens of the same material were also subjected to a torsion test. The samples were approximately 0.90 in. in diameter and 5 in. long between gage points. One specimen was ground to size before annealing, the other turned to size after annealing. Stress-strain diagrams from the two tests are given in Fig. 6.

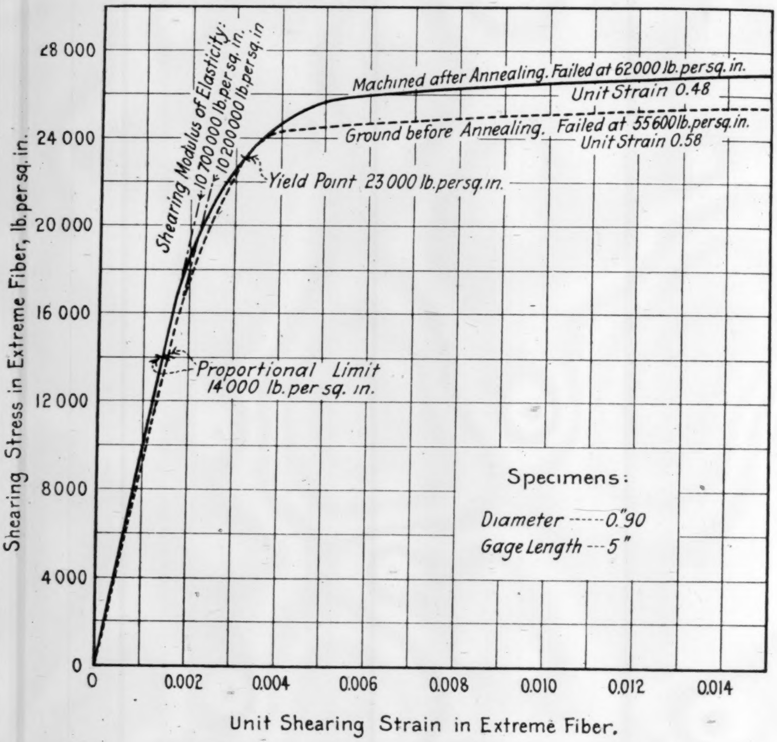

FIG. 6.—Stress-Strain Diagram of Malleable Cast Iron in Torsion.

HARDNESS.

The Brinell hardness of malleable cast iron has been observed to range from 101 to 145, the average value being approximately 110. Shore scleroscope readings on malleable iron with a Brinell hardness of 102 will average about 15. All attempts made to correlate the Shore and Brinell hardness with machining quality have been entirely without success. The Brinell number varies approximately with the tensile strength, and inversely with the carbon content of the material, as should be expected.

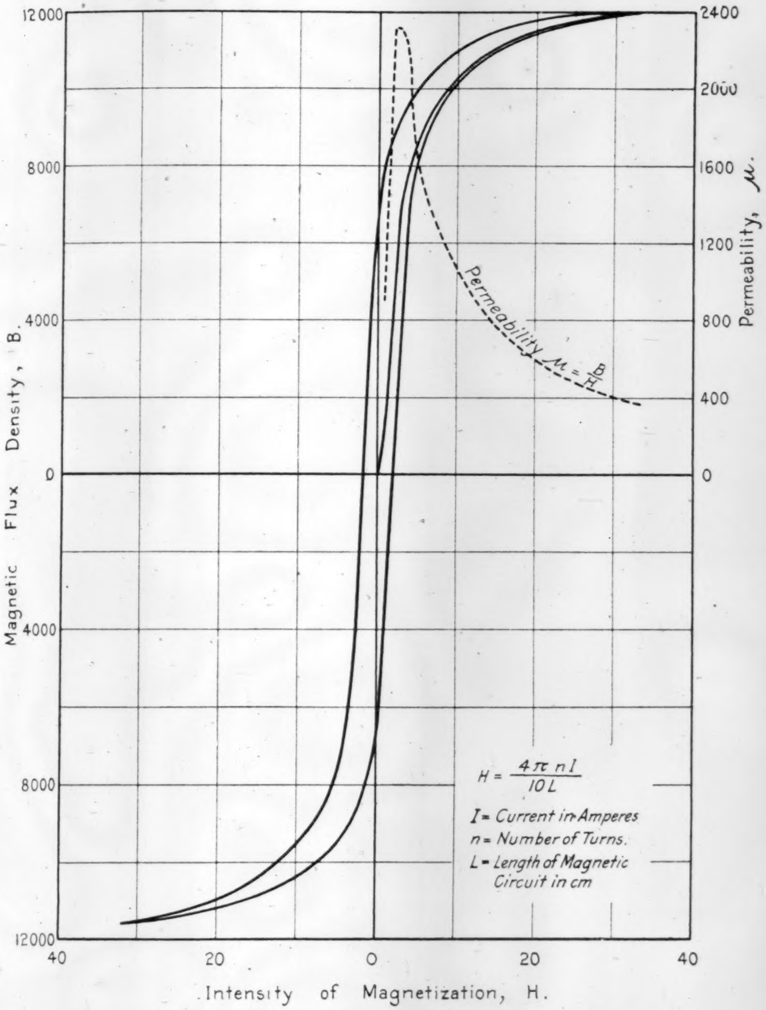

FIG. 7.—Magnetic Properties of Malleable Cast Iron.

ELECTRO-MAGNETIC PROPERTIES.

The magnetic properties of the product have been rather extensively studied by the National Malleable Castings Co., both in its own electrical laboratory and before that time in cooperation with Dr. E. S. Johonnott at Rose Polytechnic Institute. The magnetization curve and hysteresis loop shown in Fig. 7 are plotted from some of the earlier observations. The test was made on a ring-shaped specimen having a cross-section about 1 in. square and a mean diameter of about 4 in.

The specific resistance of a single average sample of the product has been determined as 0.000041 ohms per centimeter cube at 75° F.

RESISTANCE TO IMPACT.

The only quantitative data available to the writer indicate that the following results were obtained on an average product:

On the Charpy Machine test specimens 10 mm. square and 53.3 mm. long, with a 45-deg. V-notch 3 mm. deep at the center, absorbed $7\frac{1}{2}$ ft-lb. of energy in breaking. Tests made on an Olsen Machine on specimens of the cantilever type, 0.45 in. in diameter having a 45-deg. V-notch 0.122 in. deep, 1.10 in. from the end, held in the grips in such a manner that the notch was even with the jaws, and impact taking place $\frac{5}{8}$ in. from the end, indicated an average of 13 ft-lb. of energy absorbed.

The National Malleable Castings Co. has not investigated this property.

DENSITY.

Malleable iron will, of course, vary in density with the percentage of carbon. In Fig. 8, curve *A*, is plotted the variation of specific gravity referred to the carbon content of the original hard iron. The samples from which these data were obtained may be expected to be approximately 0.5 per cent lower in carbon than the original hard iron. The utmost care was taken to avoid any shrinkages, blowholes or other mechanical defects in the samples.

In case the density is to be used for the computation of the weight of a casting of a given design, curve *A* is not directly applicable. Malleable castings from a given pattern vary somewhat in size. This variation arises from differences in carbon content and heat treatment. All graphite-free iron castings shrink exactly the same amount. This fact has been very carefully checked by the National Malleable Castings Co. by measurements of the contraction in freezing and cooling of alloys differing much more widely in chemical composition than commercial malleable cast iron could possibly do. The unannealed castings from a given pattern are always of the same volume When annealed they expand a variable amount depending upon heat treatment and chemical composition. Therefore, if the original

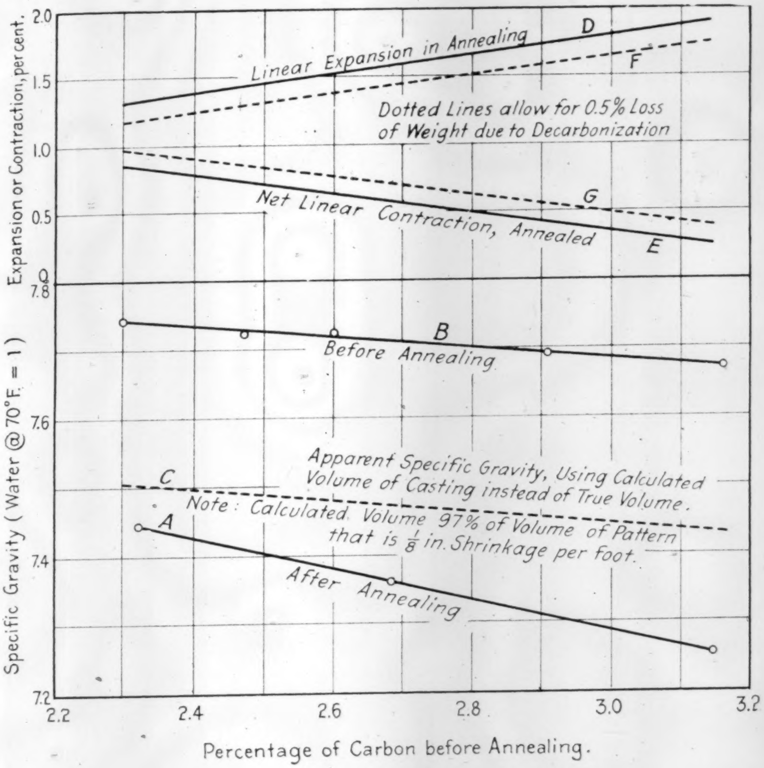

FIG. 8.—Specific Gravity of Malleable Cast Iron.

hard iron were always of the same density the variation in specific gravity would be compensated by the corresponding change in volume, and the weight of the castings would all be the same even though they would be of different dimensions.

The specific gravity of white cast iron varies with its chemical compositions as shown in Fig. 8, curve *B*. These results again are based upon samples known to be free from defects. The dotted line *C* in this figure indicates the specific gravity as referred to the expected volume of the casting made on the commercial assumption that the shrinkage of the white iron would be $\frac{1}{4}$ in. per foot and that the *net* shrinkage of the malleable casting would be $\frac{1}{8}$ in. per foot. This curve, therefore, compensates for that portion of the change in density which is compensated for in weight by a corresponding variation of volume in the casting.

Curve *D* in this figure plots the expansion in annealing corresponding to the differences of density existing between curves *A* and *B*.

Curve *E* is the difference between curve *D* and 2.14 per cent, the observed shrinkage of all white cast iron. This graph is lower than the usual commercial allowance of $\frac{1}{8}$ in. per foot corresponding to 1 per cent, but approaches that figure closely for the values of carbon around 2.40 per cent now commonly used.

Curves *F* and *G* correspond to curves *D* and *E* allowing for the decrease in weight by decarburization.

SPECIFIC HEAT.

Malleable cast iron being a mechanical mixture of iron and carbon, will have as its specific heat the average of the specific heats of the two ingredients in the proportions in which they exist in the malleable iron. The curve in Fig. 9 plots the specific heat of a mixture of 98 per cent iron and 2 per cent carbon. The results are in error to the extent that the specific heat of carbon as temper carbon is not known, and the graph is based on the specific heat of diamond. It is believed that this curve is as nearly accurate as a repetition of the work on malleable samples would have been and no attempt has, therefore, been made in our laboratories to improve upon these observations.

COEFFICIENT OF THERMAL EXPANSION.

The National Malleable Castings Co. has had occasion to design and build special equipment for the determination of changes in dimensions of castings both during the process of annealing and while freezing in the mold. In connection with these experiments there have been rendered available figures from which the expansion of malleable iron and hard iron with heat can be obtained. In Fig. 10 is shown a graph indicating the increase in length of a malleable bar with increasing temperature. The experiments were conducted on a specimen 5 in. long and the elongations measured to an accuracy of 0.0001 in. The expansion of a metal with heat generally follows a curve of the form

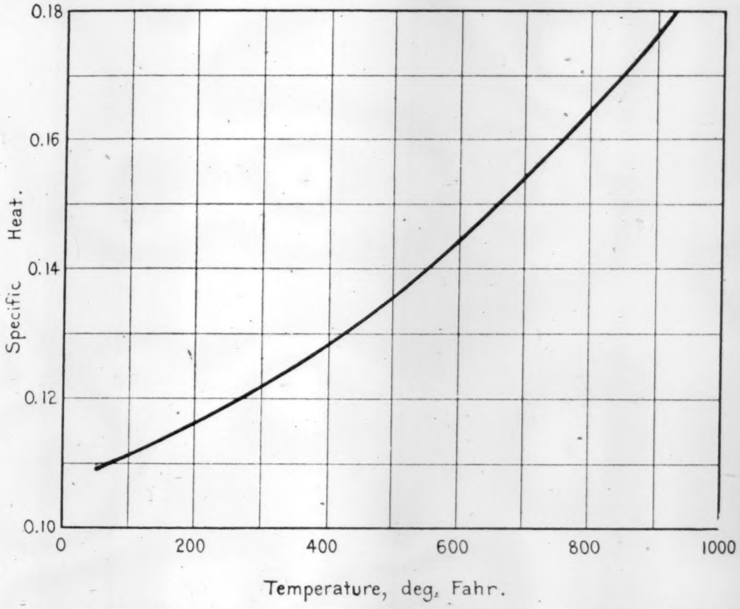

FIG. 9.—Specific Heat of Malleable Cast Iron, Calculated from Specific Heat of 98 per cent Iron and 2 per cent Carbon (Diamond).

$$L_t = L_o\ (1 + a\ t + b\ t^2),$$

in which L_o = the length at 0° C., L_t = the length at temperature of t° C., and a and b are constants.

An attempt was made to determine the values of a and b which would most nearly approximate the observed results. The dotted curve in Fig. 10 corresponds to the formula written above if $a = 0.000006$ and $b = 0.0000000125$, and this curve seems to fit the observed data almost within the limits of error of the experiment.

The experiments were not conducted beyond 1100° F., in order to keep clear of the chemical changes taking place when the critical point is passed.

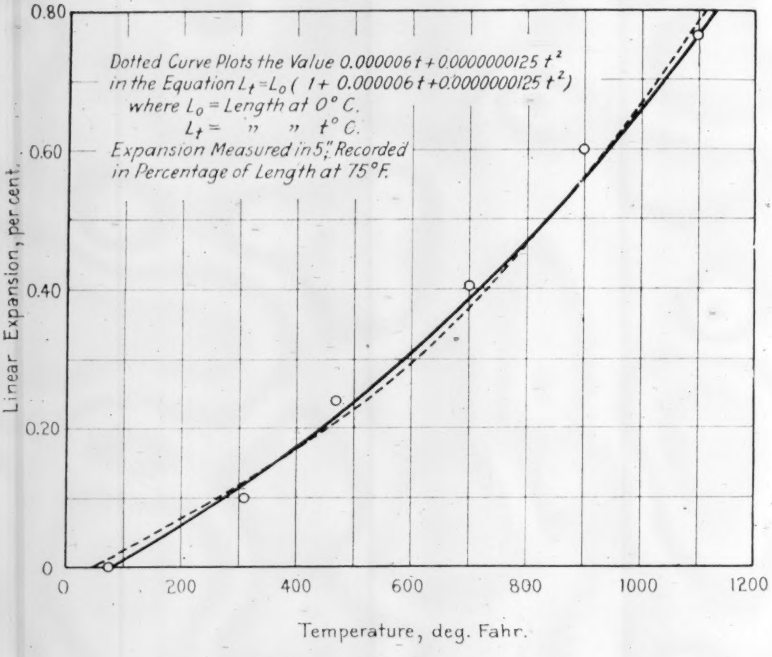

FIG. 10.—Expansion of Malleable Cast Iron.

In Fig. 11 are plotted the results of a typical experiment to determine the shrinkage of the original white cast iron. As previously pointed out in connection with the discussion of the density of malleable cast iron, all graphite-free iron castings shrink the same amount in freezing in the mold. They not only shrink the same amount, but also the form of curve correlating temperature and shrinkage is practically the same in all cases. The shrinkage curve of Fig. 11 is an average of closely agreeing results of six materials of rather widely different composition, including both normal hard irons and others of compositions far beyond those encountered in commercial malleable practice. Experiments were conducted on specimens 36 in. long, readings being accurate to about 0.002 in., The curve for exapnsion is merely the inverse of the shrinkage curve. It will be noted that the curves do not go quite to the melting point. They go,

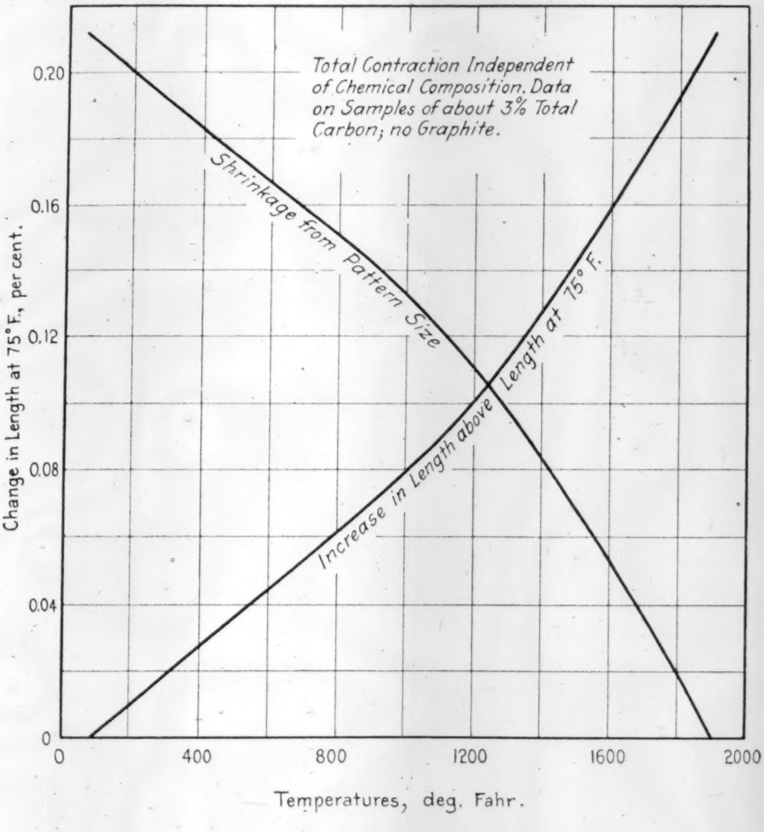

FIG. 11.—Shrinkage of White Cast Iron.

however, to that temperature at which contraction appeared to begin. Most of the white cast iron samples appeared to occupy an interval just below the melting point in which no observable contraction took place. Inasmuch as the apparatus used recorded the expansion taking place in gray iron just below the freezing point, it is assumed that no such expansion took place in the case of white cast iron.

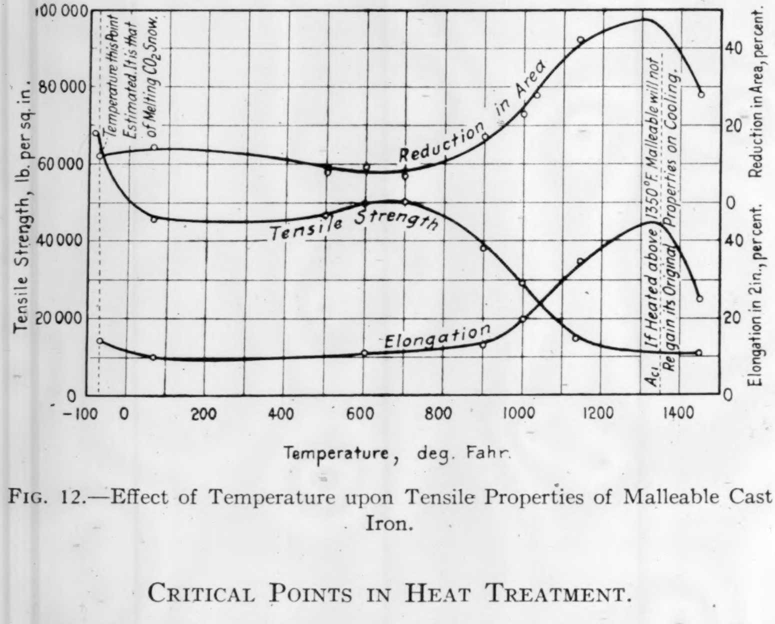

FIG. 12.—Effect of Temperature upon Tensile Properties of Malleable Cast Iron.

CRITICAL POINTS IN HEAT TREATMENT.

In connection with investigations in regard to annealing heat treatments, this company has from time to time determined the critical points of various alloys. Our experiments are not of extreme precision, but for the sake of completeness of results are included here:

	MALLEABLE CAST IRON.	HARD IRON.
Ac_1..........	1356° F. (735°.5 C.)	1350° F. (732°.5 C.)
Ar_1..........	1283° F. (695° C.)	1280° F. (693°.5 C.)

Our experiments were not sufficiently sensitive to indicate A_2 and A_3 in malleable iron.

EFFECT OF TEMPERATURE UPON TENSILE PROPERTIES.

Fig. 12 shows the tensile strength, elongation and reduction in area of malleable cast iron tested at various temperatures. Tests were conducted upon specimens 0.634 in. in diameter, ground to size before annealing. All the specimens were of the same material and of the same heat treatment. The elongation is measured in a gage length of 2 in. The results are known to be unaffected by shrinkage or other defects. The last observation at 1450° F. indicates the change of properties caused by the re-solution of carbon at temperatures above the critical point.

SUMMARY.

An attempt has been made to sum up all the reliable information at the writer's command bearing upon the physical constants of malleable cast iron. On many of the points we have in our files vastly more information than is quoted here, the material in the present paper being merely a judicious selection. On other points, and on some points not touched upon here, experimental work is in progress at the present time, and it is hoped that it may be possible to bring work on the thermal conductivity of the product and on its coefficient of friction under varying circumstances to a sufficiently satisfactory conclusion to permit of its application either in a subsequent paper or as a supplement to the present paper before the final printing of the Proceedings.

DISCUSSION.

Mr. Bean. MR. W. R. BEAN (*presented in written form*).—My discussion of Mr. Schwartz's paper will be confined chiefly to the more common physical properties or characteristics of malleable cast iron. This will be largely in the form of data confirming some of the conclusions reached by Mr. Schwartz, these data being the result of investigations carried on by The Eastern Malleable Iron Co. and by the writer previous to his association with that company.

Tensile Strength and Elongation.—The specifications now generally accepted for malleable cast iron, which are referred to by Mr. Schwartz, are being exceeded in routine tests by a very large proportion of the malleable producers and can be readily exceeded with a good margin of safety by all who will take reasonable care in the different stages of the malleable process. We could submit test records covering several thousand routine heats which would show an average elongation in 2 in. of approximately 15 per cent and an average tensile strength in excess of 52,000 lb. per sq. in., with very seldom a bar falling below 7.5 per cent elongation and 45,000 lb. tensile strength, the present test requirements.

Of possibly greater interest and certainly of more value to the engineer or user of malleable cast iron, is a test conducted during the early part of this year on tension-test specimens cut from a heavier section of malleable cast iron than it has been customary to cast. Fig. 1 is a graphical representation of this test, showing in detail the bar as cast and the position of the nine tension test specimens comprising the entire cross-section of the bar. The complete test data are given in Table I.

The completeness of the annealing is clearly evidenced by photomicrographs of the nine specimens, which showed the structure of ferrite and temper or graphitic carbon, and absence of combined carbon.

The purpose of the graphical representation of this test is to show the similarity in properties, especially tensile strength,

Mr. Bean.

of specimens cut from corresponding sections of the bar. It is not our purpose to discuss the process of manufacture in this connection, further than to say that this casting, although 3 by 3 in. in cross-section, was thoroughly annealed without

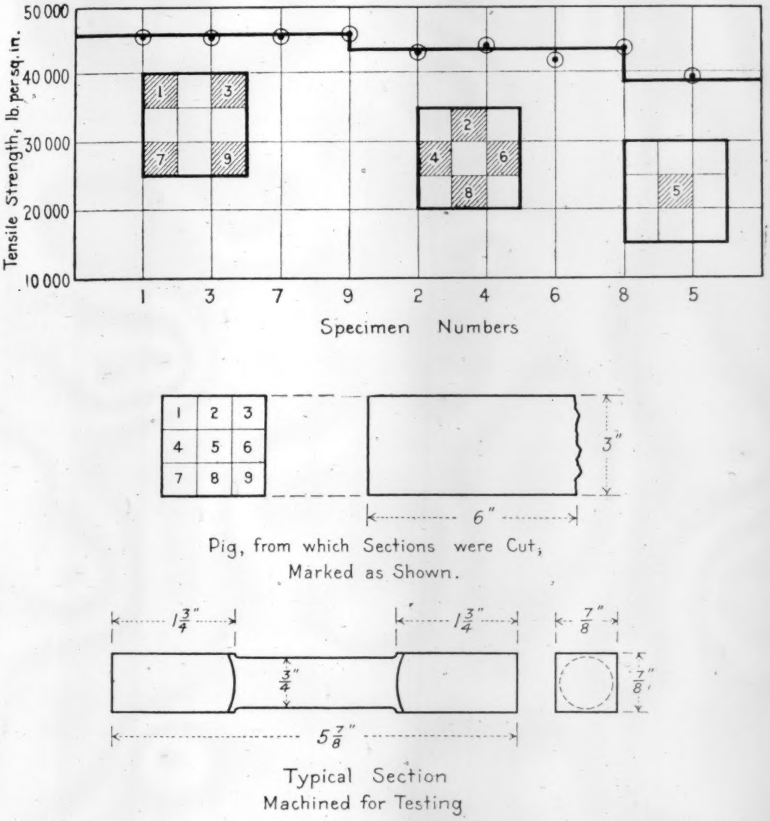

FIG. 1.—Graphical Representation of Tension Tests from a Heavy Section of Malleable Cast Iron.

any extra precaution being taken and that in spite of the heavy section of the casting and the fact that all of the skin or outer portion of the test bar was removed in machining, the test values are above or very close to those specified for malleable cast iron where maximum strength is sought. In other words, we have

Mr. Bean. here evidence to disprove two of the common fallacies regarding malleable cast iron:

First, that the strength is mainly in the skin or outer portion; and

Second, that the material is not suitable for castings of heavy section.

We are in position to supply further data or proof in substantiation of our statement regarding the relation between strength and the "skin" or outer portion of malleable iron castings, which Mr. Schwartz states he does not have in sufficient extent to be conclusive. This we submit in the form of a summary of tests of tension bars cast in pairs from 58 furnace heats, one bar being tested in the rough as annealed and the other having a finishing cut taken off before testing. In no case was the amount of metal removed less than that corresponding to a reduction of $\frac{1}{16}$ to $\frac{1}{8}$ in. in diameter, and in some of the tests the diameter was decreased $\frac{1}{8}$ to $\frac{1}{4}$ in.

TABLE I.—TEST OF TENSION SPECIMENS FROM HEAVY SECTION OF MALLEABLE CAST IRON.

Chemical analysis: silicon, 0.88; manganese, 0.30; sulfur, 0.101; phosphorus 0.194; total carbon, 2.24.

Test pieces cut from half of 3 by 3-in. test bar (See Fig. 1).

Bar finished all surfaces to remove outer portion or "skin" before being cut into test pieces 6 in. long; turned to $\frac{3}{4}$ in. in diameter.

Bar was given a normal annealing at moderate temperature and cut into test pieces on shaper with cutting-off tool. Depth of cut $1\frac{1}{2}$ in., proving complete annealing and softness throughout the section.

Specimen No.	Diameter of Specimen, in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Tensile Strength, lb. per sq. in.
1	0.749	32 455	12.0	45 914
2	0.750	31 869	10.0	42 870
3	0.750	33 318	10.0	45 450
4	0.750	36 215	10.0	43 866
5	0.750	39 859	9.0	39 859
6	0.750	38 320	11.0	41 489
7	0.750	34 861	12.0	45 835
8	0.750	37 007	11.0	43 707
9	0.750	37 211	13.0	45 631
Maximum	....	39 859	13.0	45 914
Minimum	....	31 869	9.0	39 859
Average	....	35 678	10.8	43 846

The maximum, minimum and average elongation and tensile strength are given in Table II.

It will be noted that the minimum elongation occurs on an unmachined bar, and that there is very little difference in minimum tensile strength or in fact in any of the test values. The average tensile strengths are exceptionally close. **Mr. Bean.**

If it occurs to anyone to ask regarding the difference between the test values above and those given in Table I, we would answer this question by stating that the difference is no greater and we believe a good deal less than in other cast materials from specimens similarly obtained.

Mr. Schwartz justly emphasizes the fact that malleable cast iron differs from all other commercial iron alloys in that elongation increases with tensile strength. This fact was pointed out a number of years ago, we believe, by Mr. Touceda, and while we have not undertaken to tabulate the results, we can say that our routine testing of all heats produced proves this to be a fact.

TABLE II.—SUMMARY OF TENSION TESTS.

Number of Heats.	Number of Bars	Condition of Bars.	Maximum.		Minimum.		Average.	
			Elongation in 2 in., per cent	Tensile Strength, lb. per sq in.	Elongation in 2 in., per cent.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Tensile Strength, lb. per sq. in.
58	58	Rough[1]	22.00	58 263	8.00	51 333	12.80	53 259
58	58	Machined[2]	23.00	60 060	8.50	50 241	13.20	53 234

[1] Rough bars ⅝ in. in diameter.

[2] Machined bars ½ in. and ⅝ in. in diameter.

Compression Tests.—Malleable cast iron in compression is practically indestructible so far as rupture of the surface is concerned, the action being to continually flatten out with no or only with very slight indication of rupture on the outer surface. The results of compression tests on eight samples of different sizes are given in Table III.

We did not record the elastic limit or yield point in these tests, but offer them as confirming data or evidence bearing out the statement that the material does not actually fail though compressed to a point equivalent to the destruction of any actual structural detail.

Behavior Under Cross-Bending Stresses.—When specifications for malleable cast iron were first brought out including a transverse test on bars of different thicknesses, we included this test in our regular practice and followed it for a period of some

Mr. Bean. months. It developed, however, that malleable cast iron which was not better than fair in tensile properties would readily pass the transverse test specifications. This test was therefore discontinued and we have nothing in detail to submit; but it is our observation that malleable cast iron is a reliable material under transverse load and we are disposed to accept Mr. Schwartz's conclusions in this respect.

Hardness and Machinability.—During the past year we had occasion to investigate the possibilities of the Shore scleroscope, hoping to establish a connection between this or some similar measure of hardness and the machining properties of malleable cast iron, but in this, as in the case of Mr. Schwartz, we were entirely unsuccessful.

TABLE III.—COMPRESSION TESTS.

Bar No.	Size of Bar, in.		Load, lb. per sq. in.	Reduction in Length.		Surface Crack.
	Length.	Diameter.		inches.	per cent.	
1-A.........	1.141	1.122	105 100[a]	0.260	22.7	None
1-B.........	1.129	1.134	105 190[a]	0.256	22.6	"
2-A.........	0.851	0.837	175 800[a]	0.393	46.1	"
2-B.........	0.865	0.862	171 870[a]	0.377	43.5	"
3-A.........	0.450	0.418	234 600	0.245	54.4	Very Slight
3-B.........	0.440	0.410	255 880	0.233	52.9	" "
4-A.........	0.428	0.425	305 140	0.245	57.2	" "
4-B.........	0.425	0.429	262 150	0.225	52.9	" "

[a] Loaded to maximum capacity of testing machine.

Inasmuch as the machinability of malleable cast iron is an important factor, or rather is given a very prominent place by some users of malleable castings, especially where fine threading or milling is involved, we wish to enter here a plea or protest. Many users of malleable cast iron wish to obtain light sections of strength corresponding to that of steel or wrought iron, and at the same time as readily machinable as soft gray iron. The two things are not compatible, although it is possible to machine malleable castings of the highest grade from the standpoint of strength and ductility at cutting speeds not far below those employed in machining gray-iron castings. The point we wish to emphasize is that for the sake of maximum strength and service something must be sacrificed in machinability of malleable castings.

Mr. Bean.

Mr. Schwartz has pointed out the fact that quality or strength is inversely related to the carbon content, and we now make this statement without hesitation or feeling called upon to submit proof. In this connection, I recall clearly a series of tests conducted during 1906 and 1907 which brought this fact forcibly to my attention. It was then accepted as a new development by others taking part in the tests who occupied very prominent positions in the malleable industry.

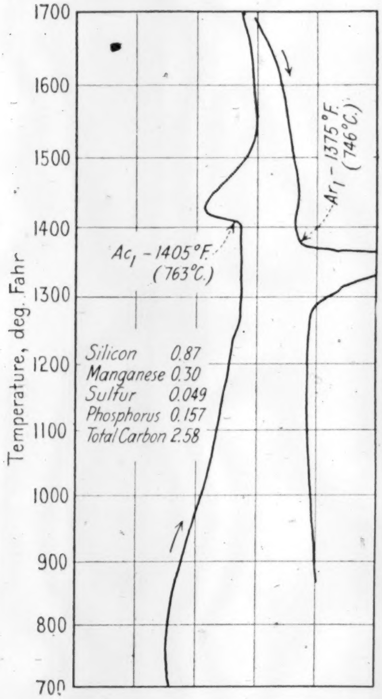

FIG. 2.—Heat Curves Obtained from Unannealed Sample of Malleable Cast Iron.

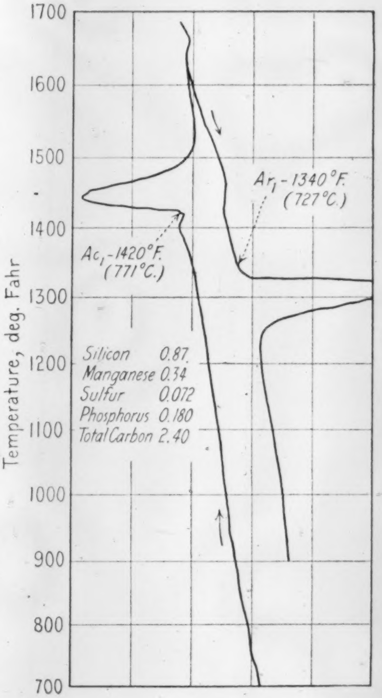

FIG. 3.—Heat Curves Obtained from Annealed Sample of Malleable Cast Iron.

It should be stated that, other things being normal, a very high carbon iron can be machined a little more readily than the lower carbon iron, even though all of the carbon is in the temper or graphitic form in both instances. Is it proper, however,

Mr. Bean. that quality should be sacrificed for a slight gain in machining speed? This would not be done in steel and other metals.

Density and Shrinkage or Contraction.—While our investigations in this field have not been as extensive as those recorded, the writer ten years ago conducted sufficient tests to convince himself and others that in the absence of graphitization in solidifying, there was no difference in shrinkage or contraction of the white iron. There is, however, as Mr. Schwartz points out, a slight difference in expansion in annealing, resulting from differences in carbon content and in annealing treatment.

Critical Points in Heat Treatment.—About ten years ago, the writer in cooperation with The Taylor Instrument Co., Rochester, N. Y., determined the Ac_1 point in malleable cast iron to be at 1375° F., which agrees closely with Mr. Schwartz's findings. This, however, has been indicated since at a temperature slightly above 1400° F. and as the duplication of the curve provides checks, we believe this to be a more accurate determination.

Through the courtesy of The Leeds & Northrup Co. of Philadelphia, we have obtained curves or charts on unannealed and annealed samples of essentially the same chemical composition. Fig. 2 is a reproduction of the curve taken on the unannealed sample and Fig. 3 of that taken on the annealed sample.

Referring to Fig. 2, it will be noted that the Ac_1 point is located at 1405° F. and the Ar_1 point at 1375° F. Referring to Fig. 3, it will be noted that on the annealed sample the Ac_1 point is indicated at 1420° F. and the Ar_1 point at 1340° F., the difference in temperature of the two points being considerably greater than on the unannealed sample.

We have stated that the two samples were of essentially the same chemical composition, which is true; but the fact that there is a difference in the carbon condition in the two samples should be given consideration, all of the carbon in the unannealed sample being in the combined state and practically all of that in the annealed sample being in the graphitic or temper carbon form, and therefore inactive below the Ac_1 point.

It should be expected, in view of the above, that the annealed sample on the heating side might act somewhat as a very low carbon steel, and in this connection the following suggestions

Mr. Bean. have been made as a possible explanation of some of the less clearly indicated points of the curve:

"In the annealed sample, it would seem as though there were a split transformation, as it is called, that is, a transformation taking place at two separate points. It would seem as though there were a transformation effect beginning at approximately 1350° and ending at 1400° F., which effect bears close similarity to the transformation effect of a very low carbon steel; in other words, as though this were the Ac_1 carbide point of a steel having say 0.01 per cent carbon. Another interpretation which might be put on it is that this point is really the Ac_2 point taking place before the Ac_1. This occurs in certain alloy steels and it is not impossible that it may be occurring here. On the cooling side of the annealed sample there is a transformation taking place through the range 1640° to 1420° F. Just what the effect which is present at around 1650° F. on the annealed sample is due to is difficult to say, and only repetition of the curve, using each time a different sample taken from the same bar, would clear up."

In the upper range of the curve above the Ac_1 point, we would expect more or less erratic results depending upon resolution of the carbon, some of which would under proper cooling conditions be reprecipitated on the cooling side.

Conclusion.—In conclusion, we are forced to the admission that even though we might be otherwise inclined, there is very little in the data submitted by Mr. Schwartz with which we can disagree. The results of our investigations seem to bring us to essentially the same points, from which it should be obvious that malleable cast iron is a reliable material when the process of manufacture is carried out under proper supervision. This happily is now the rule rather than the exception, although it admittedly did not prevail up to a comparatively few years ago.

Mr. Touceda. MR. ENRIQUE TOUCEDA (*presented in written form*).—The paper of Mr. Schwartz on "Some Physical Constants of American Malleable Cast Iron" can be considered in no other light than as a very useful and valuable contribution. The author has condensed in convenient form and made readily available for use by the engineer reliable data that should be in his possession if he proposes to make use of malleable iron castings.

Mr. Touceda. In connection with the test for hardness, the writer believes it would have been of interest to the consumer and engineer to have entered into this matter with more completeness. In the case of steels of all kinds, both raw and heat treated, of gray-iron castings and of alloys in general, the hardness test is one of great value. As is well known, this test is ordinarily used for the purpose of ascertaining the approximate tensile strength of steel as well as its cutting and mineralogical hardness. In the case of malleable cast iron, the writer believes that the hardness test is one of very limited application and of no practical value, except perhaps in a few isolated cases, and that in presenting data on hardness this point, if true, should be made clear, for the reason that the matter is not well understood even by many who are supposed to be quite well informed in regard to the physical characteristics of these castings.

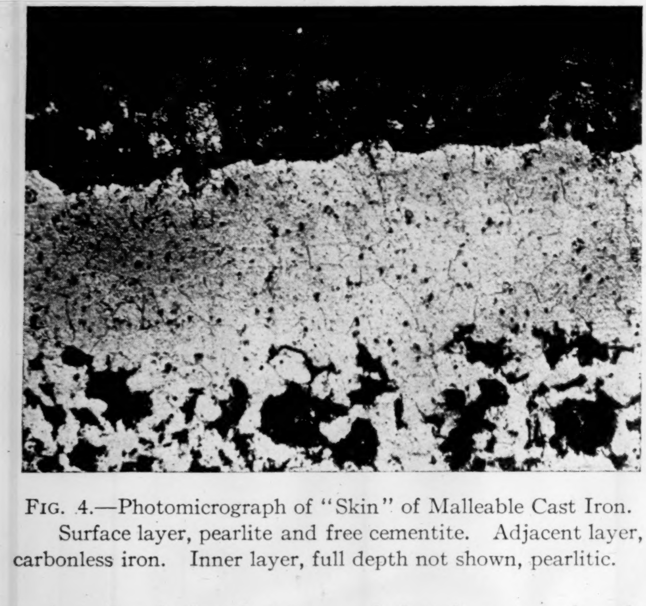

FIG. 4.—Photomicrograph of "Skin" of Malleable Cast Iron. Surface layer, pearlite and free cementite. Adjacent layer, carbonless iron. Inner layer, full depth not shown, pearlitic.

It is a well-known fact that no ferrous product can be heated to redness in the ordinary furnace atmosphere without some slight surface decarbonization taking place to a depth dependent upon how highly oxidizing the atmosphere may be

Mr. Touceda.

and the length of time the metal is exposed to it. In the manufacture of malleable iron castings, the last step in the process is to put the castings through a very lengthy annealing, or conversion operation as it might better be called. During this operation the castings are subjected as a rule to an oxidizing influence that not only results in a lowering of the total carbon content throughout the entire section, but in the elimination of almost all of the carbon to a certain depth below the surface; or, as will be explained, in the formation of a rather complex border, which, in either case, through usage, is called the "skin." In commercial castings the skin may be of a composite character, that is, instead of consisting of a single border of carbonless iron, it may consist of an outer pearlitic rim, or pearlite mixed with free cementite, surrounding a ring of carbonless iron, which in turn may or may not surround another ring of pearlite, the former condition being illustrated in Fig. 4; or it may consist of a surface ring of carbonless iron surrounding an inner pearlitic ring as illustrated in Fig. 5; or again, it may consist simply of a straight decarbonized border. If the castings are not to be machined, the tension

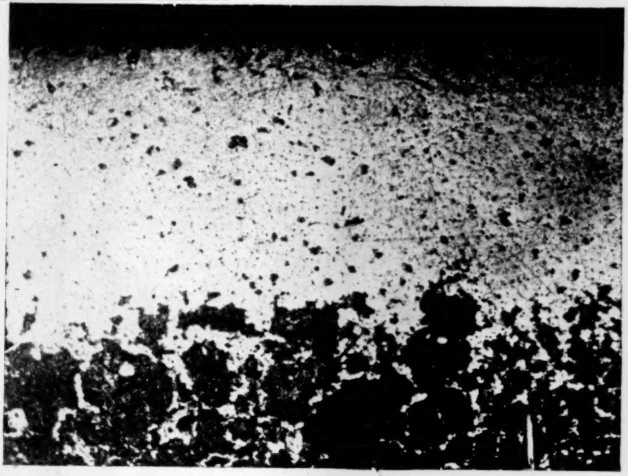

Fig. 5.—Photomicrograph of "Skin" of Malleable Cast Iron.
Surface layer, carbonless iron. Inner layer, full depth not shown, pearlitic.

Mr. Touceda. test furnishes sufficient data as to the probable softness and ductility of castings; while if the castings are to be machined, the writer is satisfied that it is practically impossible to satisfactorily ascertain through the use of a Shore or Brinell instrument whether it can be machined with ease or difficulty.

Those who have used the Shore instrument know that the results obtained with it are unreliable unless a very smooth surface is prepared upon which the hammer is to rebound. In those cases in which the skin of the castings consists of a hard pearlitic or cementitic layer, the necessary smooth surface for test can be secured only after this layer has been practically removed, owing to its limited depth, and this is particularly true if, as generally happens, the surface of the casting is curved. In such cases it is the machining of this border that dulls the tool and cause the complaint that the castings are hard. On the other hand, if the Brinell instrument is used no accurate estimate of the cutting hardness can be obtained in the case referred to, for the reason that the ball will simply break through this outer layer and penetrate the softer carbonless metal which is usually sandwiched between it and the core.

If a mixed shipment of well and incompletely annealed castings is received by a manufacturer, the lot could be tested for Brinell hardness and the two kinds separated, in which case the test would prove of value; but such occurrences fortunately are rare. Data obtained by either instrument would be useful in cases where it was required to ascertain the hardness of the metal other than that contained in the skin. Such tests would be particularly useful if made on the machined surfaces of malleable iron castings that are to be used for bearings, or when it is desired for certain reasons to ascertain the hardness of any casting after the skin is removed; but when applied to the unmachined casting very little if any information can be gathered from such tests. In those cases in which castings are annealed in a packing so inert and dense that oxidizing influences are absent, either instrument could be used to good advantage.

Mr. Schwartz. MR. H. A. SCHWARTZ (*Author's closure, by letter*).—With reference to the very interesting discussions submitted in writing by Mr. Bean and Mr. Touceda, the author would say that he is naturally much gratified by the agreement of the experience of these gentlemen with the conclusions reached in his paper.

Mr. Schwartz.

The very interesting series of experiments conducted by Mr. Bean regarding the removal of the "skin" of malleable iron as it affects the tensile strength, supplies data in a form not available to the author at the time of writing his paper. Tests of this character have to be made under very carefully controlled conditions in order to eliminate variations due to shrinkage and rate of cooling of the original casting, and from the uniformity of his results Mr. Bean seems to have succeeded admirably in securing accurate data. The effect of increased size of casting as distinguished from the effect of the "skin" is well exemplified by the tests quoted by Mr. Bean, made on different portions of the cross-section of a 3 by 3 by 6-in. block.

Mr. Bean's statement regarding the discovery that carbon was the primary controlling element in affecting the quality of malleable iron, is borne out by the author's experience. This fact was discovered in the National organization in 1904, and was at that time received with a good deal of skepticism by many people having very considerable knowledge of the subject. Whether or not others had previously discovered the same fact, the author can not say. No publication, however, had been made of this observation, so far as he knows.

The critical points determined for Mr. Bean by the Leeds & Northrup Co. are notably higher than the author's figures. He is, however, convinced that the working conditions in these later experiments are more conducive to accurate results than his own original data. From other evidence than thermal critical points, however, the author is pretty sure that the point Ac_1 can not be far above 1400° F. The absence of any indication of the A_2 and A_3 points is interesting as confirming the same observation by the author.

Mr. Touceda's presentation of the reason why hardness tests are inadequate as a measure of machinability is particularly of interest. The author would submit in addition, that since the Brinell test measures practically the tensile strength of the material, and the scleroscope the elastic limit, this furnishes an additional reason why these two tests are not of advantage, since there is no necessary direct quantitative connection between either of these properties and machining hardness.

THE BEHAVIOR OF WROUGHT MANGANESE BRONZE EXPOSED TO CORROSION WHILE UNDER TENSILE STRESS.

By P. D. Merica and R. W. Woodward.

SUMMARY.

Specimens of wrought manganese bronze rods were exposed in special test frames to corrosion in water and moist air while at the same time under tensile stress, with the object of determining the maximum safe stresses for this material under these conditions. While the period of exposure was only two years, and the initial condition of the test bars was not normal in that the initial stresses had been removed by a low temperature anneal, the results of the tests are capable of some general interpretations.

None of the test bars fractured within this period under stresses below the proportional limit, and four of the bars withstood corrosion under stresses which produced slight yielding and permanent set when first applied.

Fracture did not occur under stresses less than 35,000 lb. per sq. in.

One specimen with a proportional limit of 35,000 lb. per sq. in. fractured under a tensile stress of approximately 40,000 lb., and another with a proportional limit of 42,500 lb. fractured under a stress of approximately 43,000 lb.

These tests indicate that the proportional limit is to be regarded as the maximum safe tensile stress under these conditions for bronze of harder tempers, but that it is not certain that this limit may not be slightly exceeded in materials which are soft; that is, free from work hardness.

THE BEHAVIOR OF WROUGHT MANGANESE BRONZE EXPOSED TO CORROSION WHILE UNDER TENSILE STRESS.

By P. D. Merica and R. W. Woodward.

In the course of a previous investigation by the authors[1] of a series of failures by fracturing of brass and bronze bolts, it was suspected that many cases of such failure were due not to defective material but to the fact that the bolts had been overstressed in service. Careful examination of these bolts revealed a normal and sound structure and satisfactory mechanical properties; the bolts were comparatively free from initial stresses which would have caused corrosion cracking. No other cause of failure could well be assigned other than that they had actually been overstressed in tightening up.

The question was thus raised, what service stresses may with safety be applied to physically normal wrought brass and bronze of the types ordinarily used for structural purposes? The failed bolts in question had probably not been stressed above from 15,000 to 20,000 lb. per sq. in.; their tensile strength was about 60,000, their yield point about 30,000 lb. per sq. in. The service stresses were thus presumably not above the yield point.

Jonson[2] in a most interesting investigation showed that brass rods exposed to the action of concentrated ammonium hydroxide and subjected at the same time to the very gradual application of tensile stress would break with little elongation at any values of the stress greater than the yield point of the material. Fracture occurred within from 6 to 20 days.

The effect of combined tensile stress and surface corrosion by this solution is therefore apparently to decrease the stress at which fracture will occur.

The corrosive action of this solution is very severe and yet many, including the authors, believed that its action under these conditions was not different in principle from that of water or moist air in which brass or bronze bolts might actually be placed in service, but only more rapid. It was believed that Jonson's work demonstrated that wrought brass or bronze could be used only for very low stresses and with high factors of safety, whenever corrosion was to be expected. In view of the fact that these materials would supplant steel usually only because of their superior resistance to corrosion, the verdict of the work seemed to limit very largely the usefulness of brass and bronze for structural purposes at least until more reassuring information concerning their behavior in service might be obtained.

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[1] P. D. Merica and R. W. Woodward, "Failure of Brass," *Technologic Paper No. 82*, Bureau of Standards, 1917.

[2] E. Jonson, "The Fatigue of Copper Alloys," *Proceedings*, Am. Soc. Test. Mats., Vol. XV, Part II, p. 101 (1915).

The authors have therefore undertaken to discover whether corrosion by water and moist air will produce the same effect in combination with the simultaneous application of tensile stress as that by ammonium hydroxide. Bars of wrought manganese bronze were exposed to corrosion in water and moist air, while at the same time under tensile stresses of different values. Although the period of exposure has been to date only two years, it is thought that a report of the behavior of these bars during that relatively short period will be of interest to those using and manufacturing this material.

Since much longer periods than the few days of Jonson's tests were contemplated, small test frames were used for these tests rather than standard tension testing machines for the application of tensile stress to the specimens. Twelve such frames were made in each of which a brass bar specimen could be placed in tension of any required amount, and the value of the stress determined by strain-gage measurements on a steel reference bar placed "in series" with the brass test specimen; that is, such that the same total load was borne by the steel reference bar as by the test specimen.

A sketch of the frame used is shown in Fig. 1 and photographs are shown in Figs. 2 and 3.

Each frame consists of two blocks of steel, *a a*, which can be braced apart by the two rods, *b b*, of which one end is secured by pins, *d d*, against rotation while the other fits in the bored holes, *e e*. The brass specimens and the steel reference bars are threaded at the ends and secured by nuts, *c c*, at the ends and by the coupling nut, *i*, at the center. A ball and socket joint is provided at *f f*, to secure axial loading. The center member of these frames, consisting of the steel reference bar and the brass test specimen, can be placed under a tensile load of any desired value by the adjustment of the nuts, *g g*, against the block *a*.

The test specimens were cut from $\frac{3}{4}$-in. round bars; they were 11$\frac{3}{4}$ in. long and 0.50 in. in diameter and had standard $\frac{3}{4}$-in. threaded ends. The steel reference bars for the extensometer measurements were also 11$\frac{3}{4}$ in. long, were of two diameters, 0.420 and 0.350 in., and had also standard $\frac{3}{4}$-in. threaded ends.

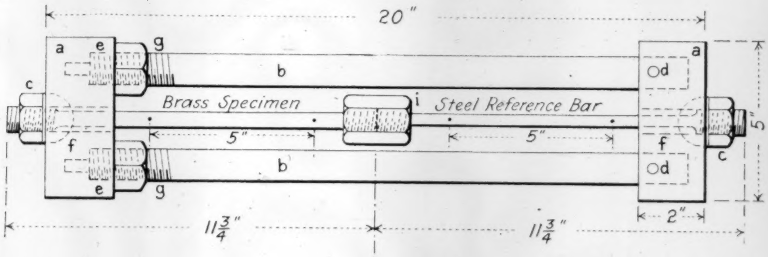

FIG. 1.—Frame Used in the Stress-Corrosion Tests.

An alloy steel rod kindly furnished by the Midvale Steel Co. was used for the preparation of the steel reference bars. This was heat-treated to produce a high elastic limit and the section of the rod was so chosen as to allow of the utilization of the full elasticity of the rod in each individual measurement of stress.

MATERIALS USED FOR TEST.

In this first series of tests only one type of brass was used, namely, manganese bronze. The American Brass Co. very kindly furnished $\frac{3}{4}$-in. round rods of this material in three tempers or degrees of hardness, Nos. M 237, M 238 and M 239, as well as the results of chemical analysis and of mechanical tests of the rods. These data are given in Table I.

These rods as furnished were in a condition of more or less initial stress, and as it was not desired to have the interpretation of the results of these tests complicated by their presence, the rods were annealed between 285 and 315° C. in a salt bath for five hours and slowly cooled. This temperature, it has been shown,[1] is sufficient to relieve initial stress in manganese bronze but does not markedly soften the material.

TABLE I.—CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF THE THREE SAMPLES OF WROUGHT MANGANESE BRONZE USED IN THE TESTS.[1]

CHEMICAL ANALYSIS.

Elements.	Rods No. M 237.	Rods No. M 238.	Rods No. M 239.
Copper, per cent	56.64	56.87	56.60
Zinc,[2] per cent	40.94	41.07	41.01
Tin, per cent	1.26	1.20	1.18
Lead, per cent	0.12	0.08	0.11
Iron, per cent	0.85	0.68	0.91
Manganese, per cent	0.19	0.10	0.19

MECHANICAL PROPERTIES.

Tensile strenght, lb. per sq. in	84 700	89 050	101 650
Yield point, lb. per sq. in	44 050	59 550	73 350
Elongation in 2 in., per cent	29	22	14
Reduction of area, per cent	25	19	10
Brinell hardness[3]	117	137	158
Scleroscope hardness[3]	36	43	49

[1] These values were furnished by the American Brass Co.

[2] By difference.

[3] Taken at the center of the section of the rod.

Determination of the proportional limit of a bar of each group after this annealing showed the following results:

	PROPORTIONAL LIMIT.
No. M 237	25 000 lb. per sq. in.
No. M 238	35 000 " "
No. M 239	42 500 " "

The moduli of elasticity of all of the bars were practically the same, namely, 16,000,000 lb. per sq. in.

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[1] *Loc. cit.*

Procedure of Test.

From each group of brass rods of the same temper four test specimens were prepared. These were placed in the frames and tensile stresses of different values, given in Table II, applied to them. Three specimens of each group, or a total of nine, were exposed to corrosion. Of each group one specimen was stressed just to the proportional limit, one was stressed to a value of the stress just above the proportional limit, and one to a value just below it. Three test specimens, one of each group, were stressed just above the proportional limit, and then covered with paraffin as a protection against corrosion; these specimens were preserved in the laboratory as comparison specimens during the period of test.

Table II.—Proportional Limits of the Test Specimens and Approximate Test Stresses Applied to Them.

Frame No.	Specimen No.	Proportional Limit, lb. per sq. in.	Approximate Test Stress, lb. per sq. in.
1	M 237-A	25 000	15 000
2	M 237-C	25 000	25 000
3	M 237-D	25 000	30 000
4	M 238-A	35 000	20 000
5	M 238-C	35 000	35 000
6	M 238-D	35 000	40 000
7	M 239-A	42 500	25 000
8	M 239 B	42 500	42 500
9	M 239-C	42 500	47 500
10	M 237-B	25 000	30 000
11	M 238-B	35 000	40 000
12	M 239-D	42 500	45 000

For the measurement of stress a 5-in. strain gage reading to 0.0001 in. was used, and on each bar two sets of holes for the gage points were placed on opposite sides. The difference in the strain gage reading before and after loading the bars by tightening up the nuts, *g g*, or unloading by loosening the nuts, allowed of the calculation of the applied stress. That the stresses were applied approximately axially is shown by the fact that the extensions of the two opposite fibers of each bar usually agreed in value within less than 5 per cent; in a few cases the agreement was only within 10 per cent.

The average value of the extensions on the two opposite sides was used in the calculation of stress.

After applying the desired stresses to all of the specimens in the frames, they were allowed to lie for a few days and were then re-gaged. Only insignificant changes in length and consequently of stress had occurred in that time. The frames were then wrapped in cloth and painted with red lead, and the steel reference bars covered with a layer of paraffin as a protection against corrosion. All gage-point holes were also carefully wrapped with cloth and paraffined. The portion of the brass test specimens in frames Nos. 1 to 9 between gage point holes was left bare and unprotected; the test specimens in frames Nos. 10 to 12 were paraffined.

EXPOSURE OF TEST FRAMES.

Frames Nos. 1 to 9 were then placed near the top of a water surge tank in an engine room such that they were alternately immersed in water and exposed to the air. Frames Nos. 10, 11 and 12 were laid away in the laboratory. This was done on December 22, 1916. On March 2, 1917, the frames were removed and examined. No cracks or fractures had appeared; the brass had tarnished badly. On March 13, the tensile stress in each test specimen was relieved and measured; on March 15 the test stress was again applied, measured, and on April 6 the frames were put back in the tank. On June 12 they were again removed and examined. No cracks had appeared but the corrosion had progressed and the surfaces of the test bars were of a greenish brown color. The frames were placed by error at this time outside the tank and were exposed to the fumes and smoke of the boiler room but remained fairly dry. On October 10, 1917, the frames were replaced in the tank. On March 4, 1918, they were removed for examination. Specimen No. 239-B in frame No. 8 had fractured, evidently quite recently judging by the brightness of the fractured surfaces. Fig. 2 shows the appearance of this frame and specimen after fracture. The other specimens were quite sound. All of the frames except No. 8 were replaced in the tank on March 10, 1918. On December 30, 1918, upon searching for these frames, it was discovered that about August 1, they had been removed from the tank by plumbers and placed back of it. When found, frames Nos. 2, 6 and 9 were entirely immersed in dirty water; Nos. 3, 4 and 5 were partially immersed, lying on top of the others. Nos. 1 and 7 were in another location which was dry at the time of examination. The latter frames were quite dirty as were indeed all of the frames, being covered with black mud, and they had evidently been in the water or had been sprayed with water from the hose while in that location.

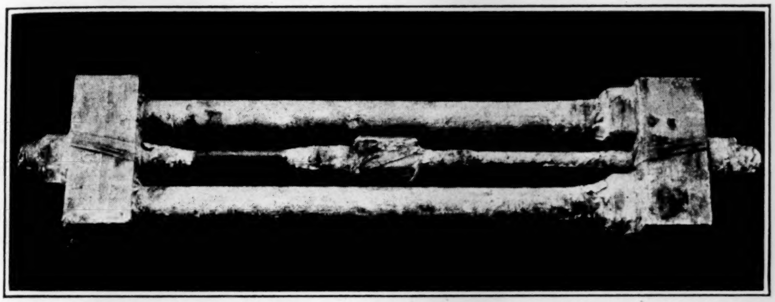

FIG. 2.—Photograph of Frame No. 8 with Specimen No. 239-B after about One Year's Exposure to Corrosion under a Tensile Stress of approximately 43,000 lb. per sq. in.

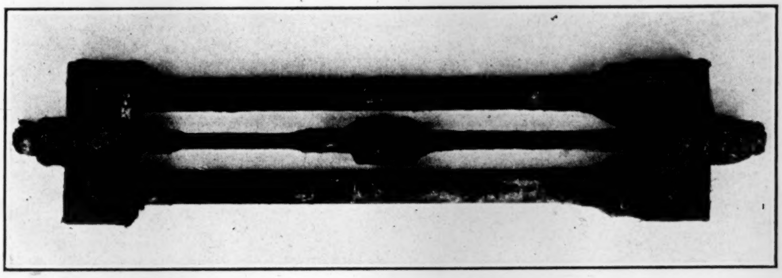

FIG. 3.—Photograph of Frame No. 9 with Specimen No. 239-C after Two Years' Exposure to Corrosion under a Tensile Stress of about 45,000 lb. per sq. in.

All of the brass specimens after washing off the mud showed that they had been moderately corroded, the surfaces being covered with a heavy dark reddish brown patina.

Specimen No. 238-D in frame No. 6 was fractured. No

TABLE III.—STRESSES AND EXTENSIONS IN MANGANESE-BRONZE SPECIMENS AS MEASURED DURING LOADING AND UNLOADING AT DIFFERENT TIMES DURING THE TEST.

Frame No.	Specimen No.	FIRST LOADING. Dec. 6, 1916.			RE-GAGING. Dec. 15, 1916.			FIRST UNLOADING. March 13, 1917.			SECOND LOADING. March 15, 1917.			SECOND UNLOADING. Jan. 3, 1919.		
		Stress in Specimen, lb. per sq. in. (1)	Stress in Specimen, lb. per sq. in. (2)	Extension of Specimen, 0.001 in. (3)	Stress in Specimen, lb. per sq. in. (1)	Stress in Specimen, lb. per sq. in. (2)	Extension of Specimen, 0.001 in. (3)	Stress in Specimen, lb. per sq. in. (1)	Stress in Specimen, lb. per sq. in. (2)	Extension of Specimen, 0.001 in. (3)	Stress in Specimen, lb. per sq. in. (1)	Stress in Specimen, lb. per sq. in. (2)	Extension of Specimen, 0.001 in. (3)	Stress in Specimen, lb. per sq. in. (1)	Stress in Specimen, lb. per sq. in. (2)	Extension of Specimen, 0.001 in. (3)
1........	M 237-A	15 000	16 300	5.1	......	......	....	17 800	17 600	5.5	14 500	16 300	5.1	14 500	13 100	4.1
2........	M 237-C	24 600	31 000	9.7	25 000	30 400	9.5	28 000	28 800	9.0	24 500	25 600	8.0	21 800	21 700	6.8
3........	M 237-D	31 000	41 000	12.8	28 900	42 000	13.1	32 300	34 900	10.9	30 200	32 000	10.0	22 400	23 600	7.4
4........	M 238-A	19 500	19 500	6.1	......	......	....	20 400	21 000	6.6	19 600	18 900	5.9	18 400	18 200	5.7
5........	M 238-C	35 000	47 700	14.9	34 800	48 300	15.1	38 400	39 600	12.4	35 300	34 000	10.6	33 400	33 700	10.2
6........	M 238-D	39 000	56 000	17.5	39 700	57 000	17.8	40 500	43 200	13.5	40 600	39 400	12.3		Broken	
7........	M 239-A	25 000	25 300	7.9	25 300	25 600	8.0	27 000	28 200	8.8	24 500	23 300	7.3	21 600	21 100	6.6
8........	M 239-B	43 600	44 500	13.9	......	......	....	43 800	44 400	13.9	42 600	41 400	12.3		Broken	
9........	M 239-C	48 600	51 200	16.0	47 200	52 800	16.5	48 500	49 600	15.5	46 500	45 100	12.9	45 100	44 100	13.8
10........	M 237-B	30 300	39 400	12.3	29 800	38 700	12.1	......	......	....	......	......	....	39 700	38 100	11.9
11........	M 238-B	40 200	49 200	15.4	39 900	49 600	15.5	......	......	....	......	......	....	43 000	43 200	13.5
12........	M 239-D	46 000	49 200	15.4	47 200	49 000	15.3	......	......	....	......	......	....	51 600	50 800	15.9

(1) This stress calculated from average of strain gage readings on steel comparison bar.

(2) This stress calculated from average of strain gage readings on brass test specimen.

(3) This is expressed directly in 0.001 in. in 5 in. (the gage length was 5 in.).

other fractures or cracks were noticed in any of the specimens. Fig. 3 shows the appearance of frame No. 9 as it was found on December 30.

The stresses in some of the frames were found to have been slightly reduced during the last exposure period. It is suspected that upon removing the frames from the tank they were dropped or otherwise roughly handled, thus causing the nuts to loosen.

In Table III will be found the values of the stress applied to the different brass specimens as measured at each loading and unloading. The first value in each case is that measured on the steel bar. In the third column is the value of the extension produced in the brass bar, and in the second column of each group, the value of the stress in that bar calculated from its own extension, using 16,000,000 lb. per sq. in. as the modulus.

It will be noticed that the values of the stress calculated from the extensions of the steel bar agree well with those calculated from the extensions of the brass bar except on the first loading. The brass specimens in frames Nos. 2, 3, 5, 6, 10 and 11 evidently yielded slightly and took a permanent set upon their first loading; the stress values in the second column therefore have no meaning in this case.

CONCLUSIONS.

In considering the results of these tests it must be emphasized that the period of exposure, two years, during which the bars have been observed is relatively short in comparison with the periods for which such materials may actually be used in service. The test bars used were given a low temperature anneal, also, in order to relieve the initial stresses, and consequently their behavior may differ during test from that of bars in which these stresses still remain. It is quite apparent, therefore, that any conclusions to be derived from these results must be regarded as quite restricted in their definite application and as more or less tentative in their more general aspects.

Within the period of exposure of two years no specimen of the wrought manganese bronze fractured under a stress below its proportional limit, and four specimens, Nos. 237-C, 237-D, 238-C and 239-C, did not fracture or crack under a stress which caused slight yielding and permanent set when first applied.

Fracture or cracking did not occur in any bars stressed to values below 35,000 lb. per sq. in. This value does not represent the highest value of the tensile stress withstood during the period of test; specimen No. 239-C in frame No. 9 was still quite sound at the end of two years while under stress of from 45,000 to 48,000 lb. per sq. in. Its behavior is considered somewhat anomalous, however, since specimen No. 239-B of the same temper fractured within about 18 months under a stress of only 41,000 to 45,000 lb. per sq. in. It is predicted that the former specimen will eventually fracture under the higher stress.

One specimen with a proportional limit of 35,000 lb. per sq. in. fractured under a tensile stress of approximately 40,000 lb. per sq. in., and another with a proportional limit of 42,500 lb. per sq. in., under a stress of approximately 43,000 lb. per sq. in.

None of the bars in frames Nos. 10, 11 and 12 which were protected against corrosion were fractured at the end of the two years.

The results of these tests seem to be partially, at least, in conformity with the conclusions reached by Jonson from his work using ammonium hydroxide as a corroding medium. His conclusion was that brass or bronze might not be subjected to corrosion (in ammonium hydroxide) while under a tensile stress greater than 20,000 lb. per sq. in. or greater than 5000 lb. per sq. in. above the yield point, without danger of failure. The authors' tests indicate that the proportional limit is to be regarded as the maximum safe tensile stress under these conditions for manganese bronze of harder tempers, but that it is not certain that this limit may not be slightly exceeded in materials which are soft, that is, free from work hardness.

Only further exposure tests which are now proceeding will decide this point. From the practical standpoint, it is very desirable to know whether it is permissible to tighten a bolt of brass or bronze until it yields slightly or whether rigid care must be exercised that the load applied in tightening is at no time above the yield point.

DISCUSSION.

MR. E. L. LASIER (*presented in written form*).—I have been much interested in the presentation of this subject by Messrs. Merica and Woodward and especially the suggestion in their paper that the further careful investigation of brasses and bronzes under the conditions under discussion is necessary before those materials can be used in places where strength is prerequisite, with any preconception of the results and of their efficiency. **Mr. Lasier.**

The problem of the corrosion of brasses and bronzes is exceedingly complex, involving as it does many factors. The Corrosion Committee of the Institute of Metals—which has probably investigated the subject more exhaustively and on a broader scale than any other body or individual—has pointed out[1] two distinct types of corrosion possible: "complete" corrosion, in which the constituents of the alloy dissolve simultaneously at approximately the same rate and uniformly over the surface of the metal, and "selective" corrosion (usually dezincification), in which only one constituent dissolves. At the outset, therefore, there is the factor of the effect on corrosion resistance of the constituent elements, which in itself is not easy to predict, especially when the use of complicated compositions such as, for illustration, aluminum bronze with an appreciable iron content is contemplated. Added to this factor are the questions of the effect of probable temperatures to be encountered in the service involved, the probable corroding media, the influence of the surface condition of the metal used, the effect of contact of the metal with other materials, the initial presence in the alloy used of stresses, the effect of working the metal, and many other factors including the particular one now under discussion, attention to which was called by E. Jonson,[2] and which is now reported upon (in so far as wrought manganese bronze is con-

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[1] Third Report to the Corrosion Committee of the Institute of Metals, *Journal* of the Institute of Metals, No. 1, 1916, Vol. XV, p. 41, and abstract of the Fourth Report, appearing in *The Engineer*, March 28, 1919, p. 300.

[2] E. Jonson, "The Fatigue of Copper Alloys," *Proceedings*, Am. Soc. Test. Mats., Vol. XV, Part II, p. 101 (1915).

Mr. Lasier. cerned) by Messrs. Merica and Woodward, namely, the effect of combined external loading and corrosion.

Recently I have been involved in the investigation of two failures due to selective corrosion in combination with stress, although apparently in neither case was manganese bronze the metal used.

In the first of the two instances in mind an experimental test block was made up, representing a section at the location of the outboard strut palms of one of the Navy's 110-ft. submarine chasers which was built during the War. The sample strut block consisted essentially of oak and yellow-pine frame work separating two 8 by 14-in. steel plates, $\frac{1}{8}$ in. thick; the two plates and the frame work were held together by means of five $\frac{3}{4}$-in. diameter wrought Muntz metal bolts, 10 in. in length, showing on chemical analysis 59.8 per cent copper, 0.3 per cent lead, 0.1 per cent iron, and the remainder, or 39.8 per cent, zinc (tin, nickel, and manganese not being detected). In this connection, I may say that although the bolts are called "Muntz metal bolts" because of the determined composition as just given, it will be noted that from the mechanical properties later reported, the material is very possibly rolled manganese bronze or some other similar metal in which a deoxidizer was employed but which was not detected by the analysis.

The test block was immersed in fresh water twenty days and was then removed and placed in a room in a temperature of approximately 70° F. for two and one-half days. Then one of the five bolts ruptured in the threads with such force that one end was thrown several feet distant from the test block.

Upon examination it was found that the swelling of the wood due to its immersion, which had subjected the bolts to such stresses as to cause the failure of the middle one, had caused the steel plates to crush into the wood about $\frac{1}{8}$ in., at the same time bowing out the plates at the middle. The maximum swelling of the wood itself was about $\frac{1}{2}$ in. measured on a line through the center bolt. The bolt which failed showed an elongation after fracture of about $\frac{1}{2}$ in., while the side bolts which did not fail showed a permanent elongation of about $\frac{1}{4}$ in.; this low elongation, only about 5 per cent in the case of the bolt which failed, is in agreement with the observations noted by the authors

Mr. Lasier.

and by E. Jonson,[1] that the failure of brass rods when exposed to combined stress and corrosion is accompanied by comparatively slight elongation. Upon removal from the block, the bolts showed bright surfaces for approximately two-thirds of their length, suggesting that they were held firmly in the wood for that part of their length, so that possibly only about 3 in. in length of the metal of the bolts took the stress to which they were subjected. The test block from which the bolts were removed was subsequently left in a dry room and resumed practically its original dimensions.

The bolt which failed and one of the unbroken bolts used in the test were carefully examined; the unbroken bolt will be referred to as sample U and the broken bolt as sample B. The laboratory tests made were conducted by the Bureau of Standards.

Following are the results of tests on these samples:

	SAMPLE U (Unbroken).	SAMPLE B (Broken).
Tensile strength, lb. per sq. in.	72 000	72 550
Yield point, " "	60 920	64 000
Proportional limit, " "	24 000	29 500
Modulus of elasticity, per cent	. . . . .	15 230 000
Elongation in 2 in., "	30.0	30.0
Reduction in area, "	57.9	57.8
Fracture.	silky; imperfect cup.	silky; imperfect cup.
Average Brinell hardness.	139	123

Both samples U and B were examined microscopically and appeared to possess identical structural features. The alloy had the usual Muntz metal duplex structure and the alpha and beta constituents were solid solutions of zinc and copper of different concentrations, the beta being much richer in zinc than was the alpha. Fig. 1 is a diagram showing the shape in longitudinal section of the fracture of the bolt (sample B). Fig. 2 shows the normal duplex fracture of Muntz metal in the lower part of the micrograph; the upper portion shows the selective corrosion of the beta constituent of the part marked "X" in Fig. 1, by which it is converted into a real brittle, copper-like deposit. Fig. 3 shows a crack initiated by dezincification of

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[1] *Loc. cit.*

Mr. Lasier. the beta constituent in the root of one of the threads. Microscopic examination of the edge of the fracture ("Y" in Fig. 1) shows no evidence of selective corrosion; evidently the break here has taken place because of the section having become too small after the cracks had formed at the outside by corrosion, to carry the applied load.

It will be noted that the physical properties of the two specimens B and U were approximately the same except in the proportional limit, in which respect that of B was considerably higher than that of U. The failure of the bolt B was probably initiated by the selective corrosion of the beta constituent at the root of some of the threads, being the result of corrosion under stress. The initiation of the failure at the root of the threads is in line with the suggestions made by Merica[1] that the bottom of notches or V-shaped grooves furnishes an incipient location for failure. After the cracks had penetrated to a sufficient depth the bolt broke under the action of the load. The break probably started from at least two cracks on opposite sides of this bolt, some distance apart (approximately $\frac{1}{2}$ in.) so that the fracture had a sloping face somewhat like a "shear" fracture. The difference in the proportional limit of the material in the two samples B and U (assuming that they were not changed by the tensile stress to which they were subjected when the test block was under immersion) might account for the ability of four of the five bolts to resist failure under the immersion loads.

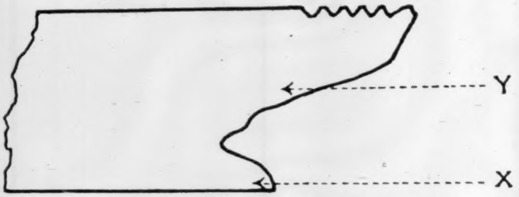

FIG. 1.—Sketch Showing Shape, in Longitudinal Section, of Bolt Fracture.

The failure of the bolt just described falls closely in line

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[1] P. D. Merica, "Failure of Brass—Effect of Corrosion on the Ductility and Strength of Brass," *Technologic Paper No. 83*, Bureau of Standards, pp. 2 and 3.

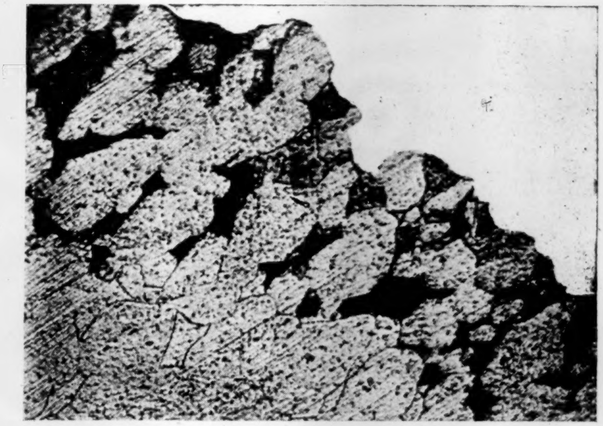

FIG. 2.—Micrograph of Part marked "X" of Fig. 1, showing Corrosion of Beta Constituent. Etching, concentrated ammonium hydroxide (× 500).

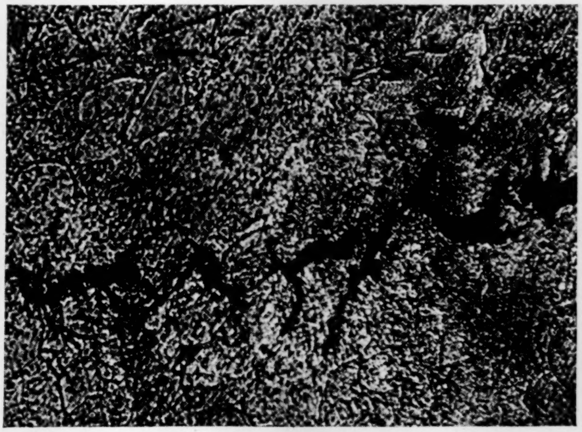

FIG. 3.—Micrograph showing Crack, Initiated by Dezincification of Beta Constitutent in Root of a Thread. Etching, concentrated ammonium hydroxide (× 500).

Mr. Lasier. with the study made by Rawdon[1] on the deterioration of Muntz metal by selective corrosion.

The second of the two instances in mind involved the failure of a cast bolt of approximately the following composition:

Copper	59.0 per cent
Tin	0.9 "
Lead	0.3 "
Iron	1.0 "
Aluminum	0.4 "
Antimony	trace
Nickel	0.4 "
Vanadium	not detected
Zinc (by difference)	38.0 per cent

While the composition would place the metal in the class of cast Muntz metal, it is possible, after due consideration of the mechanical properties given below, that it is cast vanadian bronze or some other similar metal in which a deoxidizer was employed but which was not detected by the analysis.

The bolt failed after the towing of a submarine chaser from Dubuque, Iowa, down the Mississippi river to New Orleans. Prior to the trip down the Mississippi river the three propellers of the boat were removed from the shafts and the ends of the shafts were properly protected so as to prevent damage and corrosion. During the trials of the boat at New Orleans the strut bolt in mind, which was 11 in. in length and $\frac{3}{4}$ in. in diameter, failed. Upon examination it was ascertained that the struts and bearings were out of alignment varying from $\frac{5}{32}$ to $1\frac{41}{64}$ in.; the failed bolt was therefore subjected to considerable stress. The failed bolt was carefully investigated with a view of ascertaining the characteristics of the material. Again the Bureau of Standards made the tests conducted.

The test results follow:

Tensile strength, lb. per sq. in.	53 400
Yield point, " "	20 500
Porportional limit, " "	17 500
Elongation in 2 in., per cent	7.0
Reduction of area, "	12.8

The fractures of the test specimens showed porous and unsound metal to some extent.

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[1] Henry S. Rawdon, "Typical Cases of the Deterioration of Muntz Metal by Selective Corrosion," *Technologic Paper No. 103*, Bureau of Standards.

Mr. Lasier.

In stripping tests made on two of the bolts, accompanied by nuts, a maximum load of 41,800 lb. was required to force the bolt through the nut in one test, and 32,500 lb. in another test, thus giving a mean required stripping load of 37,200 lb., which it will be noted is sufficient to develop a tensile strength of 84,200 lb. per sq. in. over an effective area of about 0.442 sq. in., corresponding to a diameter of $\frac{3}{4}$ in., the diameter of the bolt stock; the thread strength was therefore more than sufficient to develop the entire strength of the bolt.

Brinell and Scleroscope hardness values were determined and the results showed that the metal in the threaded broken piece of bolt had a Brinell hardness numeral of about 103–107 and a Scleroscope hardness of about 23.

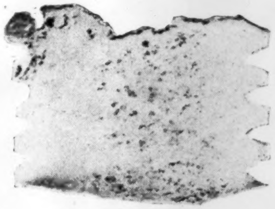

FIG. 4.—Macrograph showing Porous and Unsound Condition of Bolt. Etching, concentrated ammonium hydroxide (× 2).

Samples of the metal were examined microscopically: from the sound unthreaded portion of the bolt, from the sound threaded part of the bolt, from the part immediately back of the fracture of the bolt, and from the cast washer of the metal. The general type of microstructure of the different samples was the same in all, that is, grains of the beta constituent, which the alpha or copper-rich constituent had separated as thick pointed needles, were observed throughout. The beta crystals were also surrounded by envelopes of the alpha constituent.

The microstructure of the casting showed no unusual features in its structure. An examination of the microstructure of the sound portion of the bolt showed that the mechanical working of the metal had not materially changed its structure. Directly back of the fracture the metal was very porous and unsound, particularly throughout the central one-third of the

Mr. Lasier. bolt. This condition is shown in Fig. 4, while Fig. 5 shows the appearance of this condition under a higher magnification. Apparently this porous condition existed in the casting and was but little changed by any mechanical working the bolt may have received. In some of the fine cracks adjacent to the fracture and at the base of some of the threads there was some evidence of selective corrosion or dezincification of the beta constituent.

It is unfortunate for the purposes of this discussion that the bolt showed evidences of bad segregation, porosity and unsound structure, since in a way such conditions befog any conclusion as to the effects of selective corrosion in combination with stress. It is evident, however, that selective corrosion in combination with stress was to some extent responsible for the failure.

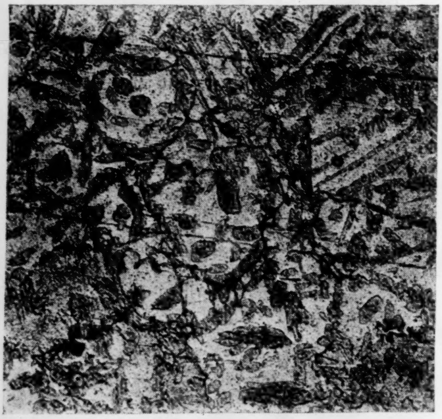

FIG. 5.—Micrograph showing Condition Noted in Fig. 4 under Higher Magnification. Etching, concentrated ammonium hydroxide (× 75).

Unfortunately no quantitative deductions can be made from the two experiences just cited. The instances are reported, however, to illustrate further the suggestion by Messrs. Merica and Woodward that the subject of the behavior of brasses and bronzes under combined stress and corrosion is one of practical importance, and to make the data obtained in the investigations available for such use as may be desired.

SOME TESTS OF LIGHT ALUMINUM CASTING ALLOYS: THE EFFECT OF HEAT TREATMENT.

By P. D. Merica and C. P. Karr.

SUMMARY.

The tensile properties and the hardness of a number of different compositions of light aluminum casting alloys have been determined, as well as the behavior under the action of alternating or repeated stresses.

The results of the tests have shown that it is possible to obtain with several compositions a casting which will have a reasonable amount of ductility together with strength as great or greater than that of the present light casting alloys in commercial use, and it is believed that there should be a real demand for an alloy of this type.

The effect of heat treatment on the mechanical properties of copper-aluminum and copper-magnesium-aluminum alloys is markedly to increase the tensile strength and hardness; with this is associated an irregular change in ductility, sometimes a decrease, sometimes an increase. The heat treatment of light aluminum alloy castings of such compositions seems to offer interesting commercial possibilities.

There seems to be no marked difference in the resistance of different compositions to the action of repeated stress; each of three compositions which were investigated withstood 10,000,000 complete reversals at a maximum fiber stress of 7000 lb. per sq. in.

The microstructure of the alloys was studied and correlated with the mechanical properties and type of fracture.

SOME TESTS OF LIGHT ALUMINUM CASTING ALLOYS: THE EFFECT OF HEAT TREATMENT.

By P. D. Merica and C. P. Karr.

During the past eighteen months a number of experimental heats of different compositions of light aluminum casting alloys have been poured at the Bureau of Standards foundry, and mechanical and corrosion tests made of the test bar castings. These tests have not been of a particularly systematic nature but have been directed at different times toward different objectives, such as the development of a suitable ductile casting alloy, the determination of the resistance of standard alloys to alternating stresses, the effect of heat treatment on the mechanical properties of casting alloys, and the study of the effect of type of test bar. Much of the work was done in connection with the activities of the sub-committee on aluminum of Committee B-2 on Non-Ferrous Metals and Alloys of the American Society for Testing Materials. The grouping of the results of these tests and discussion of them within the scope of one paper is somewhat arbitrary, but constitutes perhaps the best presentation of some of the facts which have developed during the course of the investigations.

Many of the questions studied have received attention at the hands of previous investigators; a summary of all of this work together with a bibliography of it is contained in a recent publication.[1]

Preparation of the Alloys.

The alloys were all prepared with commercially pure materials: 99-per-cent aluminum, commercially pure copper, thermit manganese, pure nickel, pure spelter, and 99.9 per cent pure magnesium.

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[1] "Aluminum and Its Light Alloys," *Circular No. 76*, Bureau of Standards, 1919; also in *Chemical and Metallurgical Engineering*, 1919.

Hardeners, prepared in a crucible, were used for the introduction of these elements, as follows:

50 per cent copper, 50 per cent aluminum;
50 per cent aluminum, 25 per cent copper, 25 per cent manganese;
80 per cent aluminum, 20 per cent nickel.

In preparing a heat, the required amount of hardener together with the aluminum was placed in the crucible and melted; a No. 40 plumbago crucible was generally used. The metal was stirred with a graphite rod, the pot removed from the furnace and the magnesium added and submerged within the melt with tongs. Rock salt was added as a flux during the melting, and just before pouring an ounce or so of zinc chloride was thrown on the metal to bring up and remove the dross.

The earlier heats, H-1, H-2, E-5, E-6, E-7, A-2, A-4, E-8, E-C and D, G-1, G-2, C-15, C-16, C-17, C-18, C-19, A-30, and Z-31, were melted in an oil-fired furnace, the others in a gas-fired one. The highest temperature during melting and the pouring temperature were measured with a thermo-couple protected with iron pipe.

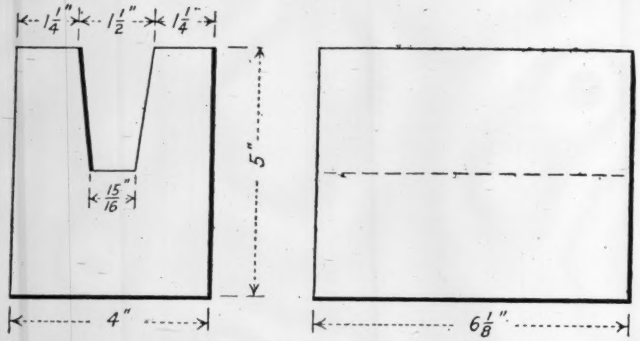
All specimens, except those of type No. 2, were poured in green sand, skin dried with the torch; those of type No. 2 were poured in core sand.

Heats X-1 and 2, XE-3 and 4, C-56, XE-5 and 6, XE-7 and 8, XE-9 and 10, C-20, C-57, C-49, C-59, C-53, E-21, E-22, H-5, H-6, Z-14, E-9, G-7, G-8, Z-15, Z-16, G-9 and G-10 were melted in a covered crucible, the others without cover.

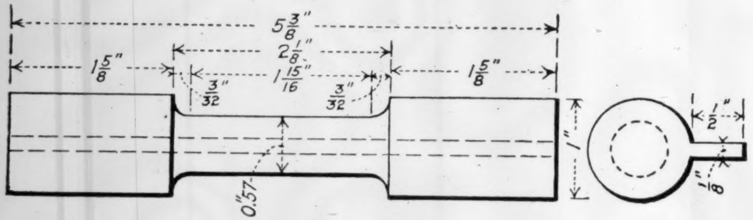
METHODS OF TEST.

All test bars for the tension test were machined to 0.505 in. in diameter over the gage length of 2.25 in. Types Nos. 1, 2, 3 and 7 (Figs. 1 and 2) were tested with wedge grips; type No. 4 had threaded ends; types Nos. 5 and 6 had shoulders with which the specimens were held in self-centering grips.

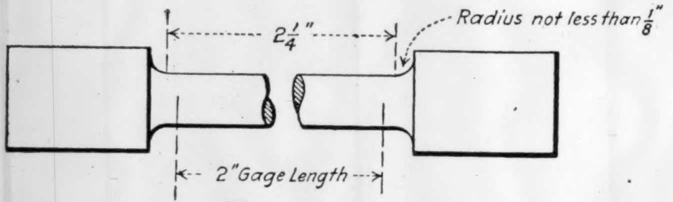
The yield point and proportional limit were determined with the Riehlé improved extensometer; the yield point was taken as that value of the stress at which the slope of the stress-strain curve was twice that of the elastic portion of it.


1 1/4"
1 1/2"
1 1/4"
15/16"
5"
4"
6 1/8"

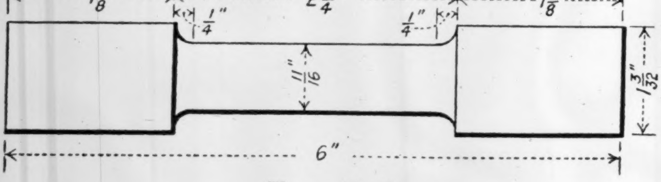
Type No. 1.


5 3/8"
2 1/8"
1 5/8"
3/32"
1 15/16"
3/32"
1 5/8"
1"
0.57"
1/2"
1/8"

Type No. 2.


2 1/4"
Radius not less than 1/8"
2" Gage Length

Type No. 2 a.


1 5/8"
2 3/4"
1 5/8"
1/4"
1/4"
11/16"
1 3/32"
6"

Type No. 3.

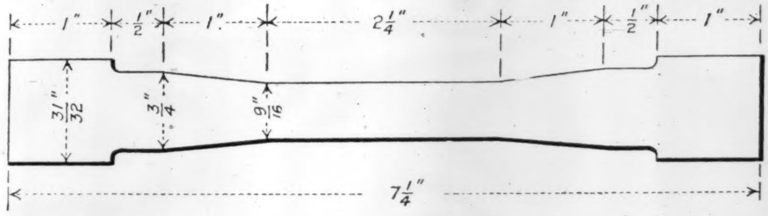
FIG. 1.—Types of Test Bars Used.

No. 1, a type often used for metals of high shrinkage.

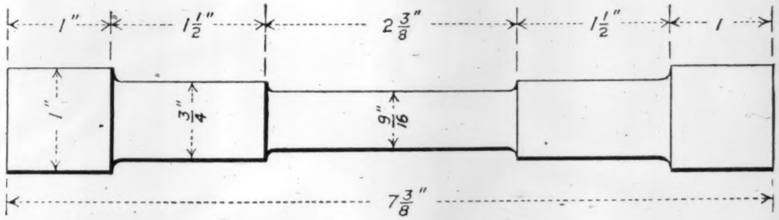
No. 2, the type recommended by the A. S. T. M. for 88:10:2 bronze; the cast bars were machined to the form No. 2 *a* and tested with wedge grips.

No. 3, a common type of test bar, poured horizontally in green sand, with gate and riser; machined to the form No. 2 *a* and tested with wedge grips.

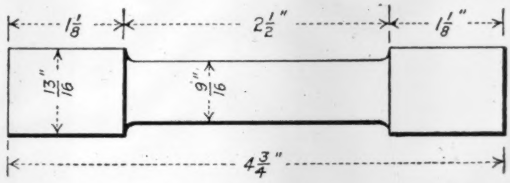
No. 4, this number is given in the tables to the same cast bar as No. 3 but machined with threaded ends and tested in a self-centering holder.


1"
1/2"
1"
2 1/4"
1"
1/2"
1"
31/32"
3/4"
9/16"
7 1/4"

Type No. 5.


1"
1 1/2"
2 3/8"
1 1/2"
1
1"
3/4"
9/16"
7 3/8"

Type No. 6.


1 1/8
2 1/2"
1 1/8"
13/16"
9/16"
4 3/4"

Type No. 7.

FIG. 2.—Types of Test Bars Used.

No. 5, shoulder type of test bar; it is machined to 0.505 in. in diameter over 2¼ in.

No. 6, shoulder type of test bar; it is machined to 0.505 in. in diameter over 2¼ in.

No. 7, small bar similar to No. 3; it is machined to 0.505 in. in diameter and tested with wedge grips.

All of these bars are cast horizontal in green sand with gate and riser.

The Brinell hardness, using a ball 10 mm. in diameter, a load of 500 kg. applied for 30 seconds, and the sceleroscope hardness with magnifying hammer, were determined on sections taken from the heads of the specimens.

Tables I to VII contain a summary of the results of the tests of all specimens as well as of the chemical compositions, pouring and melting temperatures, the data of heat-treatment and other information.

The authors are indebted to Miss H. C. Baker and Col. A. C. Krynitzky for carrying out most of the mechanical tests.

INFLUENCE OF FORM OF TEST SPECIMEN.

In Figs. 1 and 2 are shown sketches of the forms of test bars used in these experiments. Type No. 1 is often used for metals of high shrinkage, such as steel or manganese bronze. The test piece is taken from one of the lower legs and may be machined to any desired form; in these tests the type No. 2 *a* was used, the test specimens being tested with wedge grips. Type No. 2 has been accepted as standard by the American Society for Testing Materials in its Standard Specifications for 88:10:2 Bronze (Serial Designation: B 10–18); the dimensions of the bar used in these experiments do not correspond exactly to those of these specifications, however. The bar may be machined for use with wedge grips or with threaded holders; in these experiments all bars cast into this form were tested with wedge grips. Types Nos. 3 and 7 are ordinary types of test bars from which a standard test specimen of 0.505 in. in diameter may be obtained to be tested with wedge grips. The number 4 is given in the tables to a bar cast to the same dimensions as type No. 3, but machined with threaded ends. Bars Nos. 5 and 6 are of the shoulder type, and are machined to 0.505 in. in diameter. Bars Nos. 3, 4, 5, 6 and 7 were cast in pairs horizontally in green sand with gate and riser for each pair.

The test results show that type No. 1 gives very low values of the tensile strength owing to the large section of the cast piece. This type is not satisfactory for aluminum alloys. In all of the tests in which a direct comparison was made between bars of types Nos. 2 and 3, the bars of type No. 3 gave higher values both of tensile strength and elongation than those of type No. 2 (see heats E-7, Table II; G-1 and G-2, Table III; H-1 and H-2, Table IV.

The tensile strength obtained from bars of type No. 3 was always less than that from bars of types Nos. 5, 6 and 7 on the same alloy (see heats E-9, Table II; E-23, E-24, and E-27, Table V). This is undoubtedly due to the difference of section of the cast specimen; bar No. 3 is cast with a diameter of $\frac{11}{16}$ in. over the gage length, whereas the others are cast with one of $\frac{9}{16}$ in. The fact that such a small difference of section of the cast bar makes such an appreciable difference in the tensile strength shows the necessity for precise statement of this section in describing test bars in specifications for light alloys. The diameter of $\frac{9}{16}$ in., used for many of these test bars, would seem to be a most satisfactory one, as it provides amply, but with a minimum amount of machining, for obtaining the 0.505-in. diameter specimen from it.

TABLE I.—THE MECHANICAL PROPERTIES OF COMMERCIAL CAST ALUMINUM.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
A-2—A....	....	....	....	....	Fe...0.5	....	700	No. 3	AC	13 700	2 300	......	25.5	22.4	4–5	25
D...	....	....	....	....	Si...0.2	....	"	"	"	13 600	2 600	......	28.0	30.2	"	27
B....	....	....	....	....	....	....	"	"	....	13 700	2 600	......	29.0	37.3	"	26
C....	....	....	....	....	....	....	"	"	....	14 000	2 400	......	29.0	34.4	"	26
A-4—A....	....	....	....	....	Fe...0.5	....	700	No. 3	AC	12 600	2 000	......	....	....	4–5	26
B....	....	....	....	....	Si....0.4	....	"	"	....	12 500	2 300	......	....	....	"	25
C....	....	....	....	....	....	....	"	"	....	13 000	......	......	....	....	"	26

[1] AC indicates that the specimen was annealed 2 hours at 500° C. and cooled in air.

[2] Yield point defined as stress at which slope of the stress-strain curve becomes twice that of the elastic portion.

It was expected that direct comparison between the types Nos. 3 and 7, tested with wedge grips, and 5 and 6, gripped at the shoulder and self-centering, would indicate the advantage of the latter type. It is generally conceded that wedge grips should not be used for aluminum alloys which are brittle, if the best and most uniform results are to be obtained. Indeed, many

TABLE II.—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING APPROXIMATELY 8 PER CENT OF COPPER.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
E-5—M1..	8.0	....	....	....	Ha[1]....1	....	700	No. 1	....	13 600	......	......	2	....	20	57
2..	....	....	....	....	....	....	"	"	....	13 600	......	......	2	....	21	67
3..	....	....	....	....	....	....	"	No. 3	....	....	......	......	....	....	21	65
4..	....	....	....	....	....	....	"	"	....	18 500	......	......	3	....	18	65
E-6—M5..	7.2	....	....	....	Fe...0.4	....	700	No. 1	....	8 900	......	......	....	....	21	77
6..	....	....	....	....	Si...0.2	....	"	"	....	10 200	......	......	3	....	23	74
7..	....	....	....	....	....	....	"	No. 3	....	17 200	......	......	2	....	17	61
8..	....	....	....	....	Ha....2	....	"	"	....	17 200	......	......	4	....	16	61
E-7—M10.	8	....	....	....	....	....	700	No. 1	....	8 900	......	......	2	....	22	80
11.	....	....	....	....	....	....	"	"	....	14 200	......	......	3	....	21	77
12.	....	....	....	....	....	....	"	No. 3	....	13 700	......	......	2	....	11	43
13.	....	....	....	....	....	....	"	"	....	14 200	......	......	3	....	13	45
E-7—1....	8.0	....	....	....	....	....	700	No. 3	....	23 200	......	......	4	....	....	....
2....	....	....	....	....	....	....	"	"	....	23 400	......	......	4	2.0	....	....
3....	....	....	....	....	....	....	"	No. 2	....	22 800	......	......	4	....	....	....
4....	....	....	....	....	....	....	"	"	....	21 700	......	......	0	1.5	....	....
E—C.....	8.0	....	....	....	....	....	700	No. 3	....	19 500	3 500	......	3	1.0	17	66
D.....	....	....	....	....	....	....	"	"	....	15 700	3 500	......	2	1.0	16	63
E-8—12...	8.0	....	....	....	....	....	700	No. 3	....	19 500	......	......	2.5	3.6	15	57
13...	....	....	....	....	....	....	"	"	....	22 400	......	......	2.5	1.2	13	67
E-9—A....	8.6	....	....	....	....	....	700	No. 3	....	21 300	......	8 300	2	1.9	....	....
B....	....	....	....	....	....	....	"	"	....	22 300	......	11 300	1	1.9	....	....
C....	....	....	....	....	....	....	"	"	....	21 500	......	11 800	2	2.0	....	....
D....	....	....	....	....	....	....	"	"	....	19 600	......	7 500	1.3	2.0	....	....
E....	....	....	....	....	....	....	"	No. 5	....	19 500[3]	......	......	1.3	2.0	....	....
F....	....	....	....	....	....	....	"	"	....	20 900[3]	......	9 000	1.5	2.0	....	....
G....	....	....	....	....	....	....	"	No. 6	....	24 200	......	8 800	1.8	2.0	....	....
H....	....	....	....	....	....	....	"	"	....	22 800	......	8 800	1.0	2.9	....	....
I....	....	....	....	....	....	....	"	No. 7	....	19 800[3]	......	9 200	1.0	1.6	....	....
J....	....	....	....	....	....	....	"	"	....	24 000	......	7 500	1	2.5	....	....
K....	....	....	....	....	....	....	"	"	....	24 100	......	8 500	2	2.5	....	....
L....	....	....	....	....	....	....	"	"	....	24 100	......	5 500	2	2.0	....	....
E-21—E...	7.3	....	....	....	....	900	700	No. 6	....	21 900	......	4 000	2	3.0	....	....
F...	....	....	....	....	....	"	"	"	....	....	......	......	....	....	....	....
E-22—H..	8.4	....	....	....	....	900	700	No. 6	....	17 400	......	5 800	1.3	1.5	....	....
B...	....	....	....	....	....	"	"	"	....	17 200	......	6 300	1.0	2.0	....	....
C...	....	....	....	....	....	"	"	"	....	17 700	......	6 000	1.3	3.5	....	....
D...	....	....	....	....	....	"	"	"	....	14 000	......	......	0.5	2.5	....	....
C-48—A...	7.4	0.6	0.2	....	....	850	700	No. 3	AC[2]	16 200	......	......	1	0.4	26	86
G...	....	....	....	....	....	"	"	"	"	20 100	......	......	2	....	25	86
B...	....	....	....	....	....	"	"	"	....	7 900	......	......	2.5	....	26	82
F...	....	....	....	....	....	"	"	"	....	9 900	......	......	2.5	0.4	26	86

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[1] Ha is a hardener of composition given in footnote 1 of table IV.

[2] AC indicates that the specimen was annealed 2 hours at 500° C. and cooled in air.

[3] The fracture of these specimens indicates a flaw.

instances of variation of tensile properties of test bars of type No. 3 from the same heat were ascribed to the fact that they were not properly centered in the testing machine. The results of tests of bars of heat E-9, Table II, show that in this case at least the bars tested with wedge grips (No. 7) gave as good results as those of the shoulder type (Nos. 5 and 6). It is to be observed that the effect of the use of wedge grips is much influenced by the carefulness of the operator and the accuracy of alignment of the testing machine; the possibility of obtaining low results is always existent when they are used.

INFLUENCE OF MELTING AND POURING TEMPERATURES.

The influence of pouring temperature on the mechanical properties of light alloys has been the subject of much study.[1, 2] As the pouring temperature is increased the tensile strength of the alloy decreases, due largely to its larger grain size. This is illustrated in the results of the tests of heat G1–C-P, Table III, and of E-27, Table V.

The effect of the maximum temperature of melting as distinct from that of pouring has been given apparently much less attention. Two tests were made to ascertain the effect of maximum temperature of melting, using the same pouring temperature. The pot of metal was melted, allowed to cool to 700° C., and test bars cast at this temperature. The pot was then replaced in the furnace and heated to a higher temperature, removed from the furnace and bars cast at this higher temperature; the pot was then allowed to cool again to 700° C. and the remainder of the metal poured into bars at this temperature. Heats G-1, Table III, and E-27, Table V, were poured in this manner. The difference between the bars heated during melting to 850° and those to 790° C. in the case of G-1, both being poured at 700° C., was not noticeable. In the case, however, of heat E-27 a falling off in tensile strength is noticeable after heating at the higher temperature, 950° C.

The two tests, while too few to be conclusive, seem to confirm the current belief that the maximum temperature during

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[1] "Aluminum and Its Light Alloys," *Circular No. 76*, Bureau of Standards, 1919; also in *Chemical and Metallurgical Engineering*, 1919.

[2] H. W. Gillett, "The Influence of Pouring Temperature on Aluminum Alloys," Eighth International Congress of Applied Chemistry, 1912, Section II, 2, p. 105

TABLE III.—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER AND MANGANESE.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
G-1—M14	2.6	....	0.8	....	Fe...0.5	....	700	No. 1	....	14 000	......	......	6	....	12	45
15	....	....	....	....	Si...0.2	....	"	"	....	14 000	......	......	4	....	12	50
16	....	....	....	....	....	....	"	No. 3	....	21 000	......	......	7	5.4	11	48
17	....	....	....	....	....	....	"	"	....	19 100	......	......	6	4.9	11	48
G-1—1	2.0	....	1.0	....	....	....	700	No. 3	....	19 300	......	......	6	4.5	14	50
2	....	....	....	....	....	....	"	"	....	19 300	......	......	5	5.0	14	50
3	....	....	....	....	....	....	"	No. 2	....	17 900	......	......	3	4.0	12	50
4	....	....	....	....	....	....	"	......	....	16 900	......	......	2	5.5	13	54
G-2—1	3.0	....	0.9	....	....	775	700	No. 3	....	20 500	......	......	4	10.0	14	54
2	....	....	....	....	....	"	"	No. 2	....	19 200	......	......	2	6.5	13	55
3	....	....	....	....	....	"	"	No. 3	....	21 100	......	......	5	5.0	12	53
4	....	....	....	....	....	"	"	No. 2	....	19 000	......	......	3	4.5	....	50
G-1—C	2.0	....	1.0	....	....	800	700	No. 3	....	18 700	3 500	......	5	2.5	....	48
D	....	....	....	....	....	"	"	"	....	19 900	3 500	......	5	4.0	10	45
H	....	....	....	....	....	"	"	"	....	19 400	1 500	......	5	4.5	10	45
I	....	....	....	....	....	"	"	"	....	18 600	1 750	......	6	3.5	10	46
K	....	....	....	....	....	"	"	"	....	19 700	2 250	......	6	5.0	11	46
L	....	....	....	....	....	"	"	"	....	18 900	2 400	......	5	3.5	10	44
M	....	....	....	....	....	850	850	"	....	12 100	4 250	......	3	2.0	....	44
N	....	....	....	....	....	"	"	"	....	13 100	5 000	......	3	1.5	10	42
O	....	....	....	....	....	"	"	"	....	18 500	4 500	......	6	3.5	11	50
P	....	....	....	....	....	"	"	"	....	19 300	2 500	......	7	3.0	12	50
G-1—R	2.0	....	1.0	....	....	....	700	No. 4	AC	29 500	......	12 000	1.5	0.8	24	76
S	....	....	....	....	....	....	"	"	....	17 250	......	10 500	0.8	1.0	22	65
G-1—A	2.0	....	1.0	....	....	....	700	No. 5	....	......	......	......	....	....	....	....
B	....	....	....	....	....	....	"	"	....	22 900	......	10 000	1.6	2.0	18	63
G	....	....	....	....	....	....	....	No. 4	AC	24 900	......	......	0.8	2.0	20	73
—3	....	....	....	....	....	....	....	"	"	24 500	......	9 000	2.3	4.0	20	70
2	2.9	0.4	0.4	....	....	....	....	"	....	17 900	......	11 500	....	1.0	20	62
4	....	....	....	....	....	....	....	"	....	19 700	......	7 500	....	....	18	53
G-3—12	2.0	....	1.0	....	....	....	700	No. 3	....	23 400	......	......	3.0	2.0	12	60
13	....	....	....	....	....	....	"	"	AC	29 900	......	......	2.5	2.8	15	74
G-4—B	3.4	....	0.6	....	Fe...0.5	775	700	"	....	19 500	4 600	......	3.0	2.3	10	50
C	....	....	....	....	Si...0.4	"	"	"	....	17 500	......	......	3.0	1.6	10	52
A	....	....	....	....	....	"	"	"	AC	25 400	......	......	7.5	4.7	11	57
D	....	....	....	....	....	"	"	"	"	21 100	......	......	3.0	1.6	10	68
G-5—B	4.9	....	0.9	....	....	800	700	No. 3	....	19 200	......	......	1.0	0.4	12	66
C	....	....	....	....	....	"	"	"	....	15 700	......	......	3.0	1.6	12	55
A	....	....	....	....	....	"	"	"	AC	12 700	......	......	1.5	....	12	64
D	....	....	....	....	....	"	"	"	"	15 900	......	......	....	....	13	60
G-7—E	1.8	....	1.2	....	....	....	700	V	....	21 400	......	5 000	7.5	9.9	12	44
H	....	....	....	....	....	....	"	"	....	21 200	......	4 000	6.5	7.9	11	43
F	....	....	....	....	....	....	"	"	AC	24 100	......	5 000	6.5	8.0	12	50
G	....	....	....	....	....	....	"	"	AC	22 300	......	4 000	5.5	8.0	12	45

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[1] AC indicates that the specimen was annealed 2 hours at 500° C. and cooled in air.

TABLE III (*Continued*).—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER AND MANGANESE.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
G-8—B...	1.8	1.7	1.2	....	....	....	700	V	....	24 000	......	12 500	0.5	2.0	12	70
D...	....	....	....	....	....	....	"	"	....	24 900	......	11 000	1.5	0.9	11	74
A...	....	....	....	....	....	....	"	"	AC	30 700	......	13 500	1.0	1.0	10	74
C...	....	....	....	....	....	....	"	"	AC	31 500	......	13 000	2.0	2.0	14	70
G-9—E....	3.7	....	0.8	....	....	....	700	V	....	23 500	......	4 000	7.5	....	12	45
F....	....	....	....	....	....	....	"	"	AC	25 700	......	4 000	7.0	....	10	48
G-10—E..	1.5	....	1.5	....	....	850	700	V	....	22 800	......	4 000	13.5	13.5	....	....
F...	....	....	....	....	....	"	"	"	AC	25 100	......	4 000	7.5	8.5	....	....
G-11—E...	1.5	....	1.5	....	....	800	700	V	AC	....		......	....	....	....	....
F...	....	....	....	....	....	"	"	"	....	25 500	......	4 000	8.0	7.5	....	....
G-12—E...	1.5	....	1.5	....	....	920	700	......	....	20 000	......	4 100	7.0	11.8	....	....
F...	....	....	....	....	....	"	"	......	....	16 150[2]	......	......	2.0	....	....	....

[1] AC indicates that the specimen was annealed 2 hours at 500° C. and cooled in air.

[2] The fracture of these specimens indicated a blowhole.

melting must not be allowed to go too high, probably not over 850° C.

INFLUENCE OF CHEMICAL COMPOSITION.

The subject of the effect of chemical composition on the mechanical properties of light aluminum alloy castings has been much investigated.[1, 2, 3] The metals which are principally used to impart hardness and strength to aluminum are copper, zinc and magnesium. Each of these is soluble to a limited extent in aluminum, and it is to the increased hardness of these several solid solutions that the value of these additions is due. The present tests have been largely of alloys with copper as the principal hardening component. In this country the use of an alloy containing approximately 8 per cent of copper is very general, in fact the majority of sand castings at least are made of this composition. It is an excellent alloy for general purposes, hard and readily machined. Its only disadvantage is its brittleness; test bars will average only about 2 per cent elongation in 2 in. Castings made of it will resist wear well, and will not break under stresses which are below the yield point; they will not, however, withstand appreciable deformation without fracturing. It would seem that for many purposes an alloy might be desired which would be tougher and less fragile, such that instead of fracturing under accidental overload, it would yield slightly without failure.

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[1] "Aluminum and Its Light Alloys," *Circular No. 76*, Bureau of Standards, 1919; also in *Chemical and Metallurgical Engineering*, 1919.

[2] H. C. H. Carpenter and C. H. Edwards, "Alloys of Aluminum and Copper," Eighth Report to Alloys Research Committee, *Proceedings*, Inst. Mech. Eng., 1907.

[3] W. Rosenhaim and L. S. Archbutt, "Alloys of Aluminum and Zinc," Tenth Report to Alloys Research Committee, *Ibid.*, 1912.

A number of different compositions were tested with the purpose of ascertaining what tensile properties could be obtained with an alloy having appreciable ductility. In choosing the compositions for the alloys tested, the maximum solubility of copper in aluminum was used as a guide; this is approximately 4 per cent. Beyond this amount the excess copper is present in the form of a brittle constituent which cannot markedly increase the hardness but does decrease the ductility.

The test results of alloys G, Table III, H, Table IV, and E-23, E-24, E-26, and E-27, Table V, indicate the range of tensile properties which may be expected in a ductile alloy. It appears that there should be no difficulty in obtaining with a number of compositions the following tensile properties:

Tensile strength, lb. per sq. in................	20 000 – 25 000
Elongation in 2 in., per cent..................	5

It is to be observed that such alloys will not be as hard as the well-known one containing 8 per cent copper, and they will have a slightly higher shrinkage; low shrinkage and high hardness must be sacrificed in order to obtain the higher ductility.

One of the most striking facts apparent from a consideration of the mechanical tests of different compositions of light alloys is the hardening and embrittling effect of small additions of magnesium to alloys containing copper. This is evident from a comparison of heats C-15, C-16, C-17, and E-27, all of which contain from 3 to 3.5 per cent of copper, the first three containing in addition from 0.4 to 1.3 per cent of magnesium. With this copper content the elongation is lowered from about 8 to 2.5

per cent by the addition of magnesium, with only a slight increase in tensile strength. This fact is well illustrated also in heats G-7 and 8 and H-5 and 6. In each of these cases the metal was melted and bars poured without magnesium; thereupon the magnesium was added to the pot and additional bars poured. The tensile strength of each composition was increased by 10 to 20 per cent, and the elongation was decreased by 60 to 80 per cent by the addition of the magnesium. It seems apparent that

TABLE IV.—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER, MANGANESE AND NICKEL.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[2]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
H-1—1....	3.0	....	0.75	2.0	....	....	700	No. 3	....	21 400	......	......	0.4	4.5	15	50
2....	....	....	0.75	....	....	....	"	"	....	21 700	......	......	0.6	4.0	14	54
3....	....	....	....	....	....	....	"	No. 2	....	21 300	......	......	0.6	4.0	14	54
4....	....	....	....	....	....	....	"	"	....	21 500	......	......	0.5	5.0	14	56
H-2—1....	3.0	....	0.75	2.0	Ha[1]....1	....	700	No. 3	....	25 500	......	......	0.6	10.0	15	61
2....	....	....	....	....	....	....	"	"	....	25 200	......	......	0.4	11.0	15	62
3....	....	....	....	....	....	....	"	No. 2	....	20 600	......	......	0.4	4.0	16	61
..4....	....	....	....	....	....	....	"	"	....	25 100	......	......	0.4	10.5	14	64
H-4—1....	4.0	1.0	0.2	1.0	....	....	700	No. 4	AC	30 500	......	13 000	0.8	1.0	27	91
2....	....	....	....	....	....	....	"	"	....	25 500	......	13 000	....	1.0	25	80
H-1—A...	3.7	0.6	0.3	1.0	....	....	700	No. 4	....	......	......	......	....	....	....	....
B...	....	....	....	....	....	....	"	......	....	25 500	......	12 500	....	0.5	....	....
H-5—E...	3.1	....	0.8	1.5	....	....	700	No. 5	....	24 400	......	7 000	0.4	8.4	10	54
H...	....	....	....	....	....	....	"	"	....	25 400	......	6 000	0.6	8.5	10	54
F...	....	....	....	....	....	....	"	"	AC	27 000	......	5 000	3.5	5.0	9	57
G...	....	....	....	....	....	....	"	"	"	24 800	......	5 000	4.5	4.5	9	61
H-6—B...	3.1	0.9	0.8	1.5	....	....	700	No. 5	....	33 000	......	14 000	1.5	1.5	17	86
D...	....	....	....	....	....	....	"	"	....	27 100	......	12 000	....	....	19	86
A...	....	....	....	....	....	....	"	"	AC	29 700	......	13 000	1.0	1.9	17	86
C...	....	....	....	....	....	....	"	"	"	35 600	......	16 000	2.0	1.9	18	86
H...	3.0	....	0.75	2.0	....	....	....	......	....	27 000	......	12 500	0.8	1.5	....	....

[1] *Ha* is a hardener supplied by Major G. L. Norris of the following composition:

Vanadium	12 65 per cent
Manganese	26.69 "
Aluminum	55.93 "
Iron	1.20 "
Silicon	3.70 "

[2] *AC* indicates that the specimen was annealed for 2 hours at 500° C. and cooled in air.

high ductility cannot be obtained in cast alloys containing magnesium.

The results of the tests of heats E-23, E-24, E-26, and E-27, Table V, containing only copper, and of heats G, Table III, and H, Table IV, containing nickel and manganese in addition to copper, would indicate that tensile strengths as high as 25,000 lb. per sq. in. cannot be obtained with the use of copper alone, but that nickel or manganese must also be added. On the other hand, if a tensile strength of 18,000 lb. per sq. in. is sufficient, it appears somewhat questionable whether better results are not obtained with copper alone. The addition of manganese seems to produce more uniform test results but the resulting alloys are somewhat less ductile than those with copper alone.

Two heats of commercial aluminum were cast into test bars without the addition of hardener of any sort. The test results are given in Table I.

At one time there were two lots of notch-bar ingots in the foundry which seemed to show a marked difference in brittleness as tested quite roughly by bending the ingot. Inasmuch as the question of "brittle ingots" was a quite live one at the time, a heat of test bars of each lot was poured under the same conditions in order to ascertain whether the brittleness as so indicated would persist in the cast test bars. It will be noticed that there is a marked difference in the ductility of the bars of the two heats; the bars of the lot A-4 averaged only about 15 per cent elongation as compared with 29 per cent for lot A-2. It was, however, lot A-2 of which several ingots had been found to be brittle.[5] It is interesting to note the difference in silicon content of the two heats; the one with the high silicon content gave the low values of ductility.

EFFECT OF HEAT TREATMENT.

It is well known that alloys containing copper with or without magnesium in the forged or rolled condition may be improved by heat treatment consisting of quenching from about 500° C.

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[5] It must be observed that not all ingots of the lot A-2 were brittle, and that there was no assurance that all of the ingots were actually originally of the same melt except that they belonged to the same purchase lot.

TABLE V.—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER AND MAGNESIUM.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.				Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.	Type of Test Bar.	Heat Treatment.[1]	Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
E-23—A...	1.5	....	....	....	....	900	700	No. 3	....	18 000	......	2 800	8.5	11.5	....	....
B...	....	....	....	....	....	"	"	"	....	17 000	......	3 400	5.5	6.5	....	....
AA.	....	....	....	....	....	"	"	No. 6	....	20 000	......	2 500	12.5	16.5	....	....
BB.	....	....	....	....	....	"	"	"	....	19 500	......	1 800	11.5	13.0	....	....
X...	....	....	....	....	....	"	"	No. 7	....	16 200	......	3 900	4.0	8.0	....	....
Y...	....	....	....	....	....	"	"	"	....	19 200	......	3 500	10.5	12.0	....	....
E-24—A...	2.5	....	....	....	....	800	700	No. 3	....	....	......	......	....	....	....	....
B...	....	....	....	....	....	"	"	"	AC	17 400	......	3 000	6.0	10.5	....	....
AA.	....	....	....	....	....	"	"	No. 6	....	19 900	......	2 500	8.0	13.0	....	....
BB.	....	....	....	....	....	"	"	"	....	17 900	......	4 000	4.0	7.0	....	....
C...	....	....	....	....	....	"	"	"	....	....	......	......	....	....	....	....
D...	....	....	....	....	....	"	"	"	AC	21 300	......	3 200	6.5	10.5	....	....
(A) X..	....	....	....	....	....	"	"	No. 7	....	19 400	......	2 800	4.5	3.9	....	....
(B) Y..	....	....	....	....	....	"	"	"	....	18 100	......	2 000	5.5	10.0	....	....
E-26—B...	3.5	....	....	....	....	900	900	No. 6	....	17 800	......	5 800	4.5	7.0	....	....
BB.	....	....	....	....	....	"	"	"	....	17 300	......	3 800	3.5	5.0	....	....
C...	....	....	....	....	....	"	700	"	....	22 300	......	3 800	8.0	12.0	....	....
CC.	....	....	....	....	....	"	"	"	....	....	......	......	....	....	....	....
E-27—A...	3.5	....	....	....	....	775	700	No. 6	....	17 700	......	3 000	7.0	10.5	....	....
B...	....	....	....	....	....	"	"	"	....	18 400	......	3 000	5.5	7.0	....	....
C...	....	....	....	....	....	"	"	"	AC	21 600	......	3 300	11.0	9.0	....	....
D...	....	....	....	....	....	"	"	"	"	21 700	......	2 900	8.5	10.0	....	....
E...	....	....	....	....	....	"	"	No. 7	....	18 700	......	4 000	7.0	12.5	....	....
F...	....	....	....	....	....	"	"	"	....	18 700	......	3 000	8.0	7.0	....	....
E-27—G...	....	....	....	....	....	775	700	No. 3	....	15 600	......	4 000	4.5	6.0	....	....
H...	....	....	....	....	....	"	"	"	....	14 900	......	2 800	5.0	6.0	....	....
J...	....	....	....	....	....	950	950	No. 6	....	14 300	......	3 800	6.0	3.5	....	....
K...	....	....	....	....	....	"	"	"	....	12 900	......	3 000	5.5	7.0	....	....
L...	....	....	....	....	....	"	700	"	....	16 600	......	3 300	5.0	8.5	....	....
M..	....	....	....	....	....	"	"	"	....	14 900[2]	......	4 000	3.5	5.5	....	....
C-15—B...	3.1	1.3	....	....	Fe...0.4	....	700	No. 3	AC	18 500	7 500	......	3.0	....	22	82
D...	....	....	....	....	Si...0.3	....	"	"	"	18 200	8 500	......	3.0	1.0	17	69
C...	....	....	....	....	....	....	"	"	....	15 000	5 000	......	1.0	....	21	79
E...	....	....	....	....	....	....	"	"	....	15 700	4 000	......	2.0	....	19	76
C-16—B...	3.4	0.4	....	....	....	....	700	No. 3	AC	17 200	4 500	......	2.0	1.0	18	72
D...	....	....	....	....	....	....	"	"	FC	18 600	3 000	......	4.0	1.5	16	68
C...	....	....	....	....	....	....	"	"	....	10 900	3 500	......	2.0	0.5	17	69
E...	....	....	....	....	....	....	"	"	....	16 400	7 000	......	1.0	0.5	16	64
C-17—B...	3.1	1.1	....	....	....	....	700	No. 3	AC	18 500	......	......	2.0	....	25	89
D...	....	....	....	....	....	....	"	"	FC	13 200	5 500	......	2.0	....	22	77
C...	....	....	....	....	....	....	"	"	....	....	......	......	....	....	....	....
E...	....	....	....	....	....	....	"	"	....	19 300	8 500	......	5.0	1.0	23	82
CA-40—E..	3.0	1.0	....	....	....	....	700	No. 3	....	21 000	......	......	1.0	....	22	80
F..	....	....	....	....	....	....	"	"	....	10 400	5 000	......	3.0	....	22	79

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[1] *AC* indicates that the specimen was annealed for 2 hours at 500° C. and cooled in air.

FC indicates that after the same annealing the specimen was cooled in the furnace.

[2] The fracture of these specimens indicated a large blowhole.

TABLE V (*Continued*).—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER AND MAGNESIUM.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
C-18—B	A2	0.6	....	....	....	....	....	No. 3	AC	24 900	6 000	......	3.0	1.0	21	80
D	....	....	....	....	....	....	....	"	FC	18 600	6 000	......	2.0	....	15	69
C	....	....	....	....	....	....	....	"	....	13 600	4 500	......	....	....	17	74
E	....	....	....	....	....	....	....	"	....	18 900	6 500	......	2.0	0.5	18	74
C-19—B	2.5	1.0	0.4	....	....	....	700	No. 3	AC	31 400	......	......	4.0	2.0	23	86
D	....	....	....	....	....	....	"	"	FC	27 900	5 500	......	3.0	2.5	18	69
C	....	....	....	....	....	....	"	"	....	19 300	4 000	......	2.0	....	21	74
E	....	....	....	....	....	....	"	"	....	17 000	5 500	......	2.0	....	20	74
C-44—A	6.0	2.2	....	....	Fe...0.4	700	700	No. 3	AC	12 600	......	......	1.5	....	42	129
D	....	....	....	....	Si...0.5	"	"	"	AC	14 300	......	......	1.0	....	38	133
B	....	....	....	....	....	"	"	"	....	15 400	......	......	2.0	....	27	96
C	....	....	....	....	....	"	"	"	....	15 900	......	......	2.0	0.5	26	92
C-45—A	3.9	2.0	0.6	....	....	700	700	No. 3	AC	18 000	......	......	1.0	0.5	30	98
D	....	....	....	....	....	"	"	"	AC	11 700	......	......	1.5	....	29	92
B	....	....	....	....	....	"	"	"	....	10 700	......	......	1.0	....	25	84
C	....	....	....	....	....	"	"	"	....	10 500	......	......	1.5	....	24	80
C-47—A	3.9	0.9	0.4	....	....	875	700	No. 3	AC	16 500	......	......	1.0	0.5	25	75
G	....	....	....	....	....	"	"	"	AC	15 700	......	......	1.0	0.5	25	92
B	....	....	....	....	....	"	"	"	....	14 100	......	......	1.5	0.5	22	74
F	....	....	....	....	....	"	"	"	....	13 200	......	......	1.0	....	20	68
C-56—A	2.5	1.2	....	....	....	700	700	No. 5	AC	26 900	......	......	1.6	1.0	27	81
C	....	....	....	....	....	"	"	"	AC	28 100	......	14 000	0.8	1.2	26	82
B	....	....	....	....	....	"	"	"	....	22 700	5 600	......	1.6	1.5	20	65
D	....	....	....	....	....	"	"	"	....	21 700	......	9 800	1.5	1.6	20	60
C-57—A	2.5	0.8	....	1.9	....	750	700	No. 5	AC	31 800	......	8 000	0.8	1.0	22	80
C	....	....	....	....	....	"	"	"	"	32 300	......	6 000	0.8	1.5	25	81
B	....	....	....	....	....	"	"	"	....	26 900	......	4 000	1.6	1.5	21	75
D	....	....	....	....	....	"	"	"	....	26 300	......	12 500	....	1.0	25	68
C-20—A	2.3	1.3	1.4	....	Fe...0.4	800	700	No. 5	AC	35 000	......	12 300	2.3	3.5	28	86
C	....	....	....	....	Si...0.3	"	"	"	"	35 500	......	15 200	2.3	2.5	27	85
B	....	....	....	....	....	"	"	"	....	25 900	......	12 000	1.6	1.0	25	75
D	....	....	....	....	....	"	"	"	....	23 600	......	12 000	1.6	2.5	21	75
J-1—1	1.0	1.0	....	1.0	....	800	700	No. 3	....	24 800	......	......	1.5	1.5	....	....
2	....	....	....	....	....	"	"	"	....	25 000	......	......	1.0	1.2	....	....
3	....	....	....	....	....	"	"	"	....	25 300	......	......	1.0	0.8	....	....
4	....	....	....	....	....	"	"	"	....	22 300	......	......	1.0	1.2	....	....
J-1—E	1.0	0.7	0.8	....	....	850	700	No. 5	....	23 700	7 700	......	4.6	4.1	14	54
H	....	....	....	....	....	"	"	"	....	23 800	......	6 000	4.7	3.1	14	54
F	....	....	....	....	....	"	"	"	AC	26 500	5 300	......	4.6	3.7	20	63
G	....	....	....	....	....	"	"	"	"	26 600	......	9 800	3.1	2.1	20	61
J-2—A	1.6	0.4	....	1.4	....	825	700	No. 5	....	25 300	6 200	......	4.6	2.1	17	55
D	....	....	....	....	....	"	"	"	....	25 600	......	11 000	1.6	2.8	19	61
B	....	....	....	....	....	"	"	"	AC	26 400	......	......	3.1	2.0	19	63
C	....	....	....	....	....	"	"	"	AC	25 100	......	5 300	2.3	2.1	20	71

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[1] AC indicates that the specimen was annealed for 2 hours at 500° C. and cooled in air.

FC indicates that after the same annealing the specimen was cooled in the furnace.

TABLE V (*Continued*).—THE MECHANICAL PROPERTIES OF CAST ALLOYS CONTAINING COPPER AND MAGNESIUM.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
C-49—A...	3.3	0.8	....	....	Sn...3.6	725	700	No. 5	AC	19 900	......	......	....	0.5	23	72
C...	....	....	....	....	....	"	"	"	AC	18 300	......	14 000	0.8	1.5	26	74
B...	....	....	....	....	....	"	"	"	....	18 600	......	......	1.6	1.1	22	63
D...	....	....	....	....	....	"	"	"	....	16 000	......	13 000	0.8	3.2	19	65
C-53—A...	3.4	1.5	....	....	Fe...0.4	750	700	No. 5	AC	25 000	......	10 500	....	....	24	85
C...	....	....	....	....	Si...0.3	"	"	"	"	15 100	......	10 000	1.6	0.6	27	84
B...	....	....	....	....	Fn...4.5	"	"	"	....	20 500	......	14 000	0.8	0.5	25	84
D...	....	....	....	....	....	"	"	"	....	22 700	......	12 500	0.8	0.5	26	85
C-59—A...	2.7	0.9	....	0.2	Cd...2.8	750	700	No. 5	AC	29 500	......	12 500	0.8	....	25	78
C...	....	....	....	....	....	"	"	"	"	30 300	......	10 800	1.6	1.0	25	81
B...	....	....	....	....	....	"	"	"	....	24 100	......	8 500	1.6	2.1	17	62
D...	....	....	....	....	....	"	"	"	....	25 400	......	13 000	2.3	2.5	19	64
G-6—A...	2.1	1.1	1.1	....	....	700	700	No. 3	AC	25 700	......	......	0.5	0.4	23	87
G...	....	....	....	....	....	"	"	"	"	28 000	4 100	......	2.5	1.2	22	89
B...	....	....	....	....	....	"	"	"	....	15 600	......	......	1.0	....	17	74
F...	....	....	....	....	....	"	"	"	....	19 600	......	......	1.0	0.4	17	74
H-3—1....	3.4	1.3	....	1.7	Fe...0.5	775	700	No. 4	AC	26 600	......	......	1.6	1.0	25	84
4....	....	....	....	....	Si...0.5	"	"	"	"	26 300	......	10 500	....	0.5	27	85
2....	....	....	....	....	....	"	"	"	....	24 500	......	10 000	0.8	0.5	24	80
3....	....	....	....	....	....	"	"	"	....	24 300	......	9 500	0.8	0.5	26	80

[1] AC indicates that the specimen was annealed for 2 hours at 500° C. and cooled in the air.

and allowing to age for several days.[1, 6, 7] A number of tests were carried out to determine to what extent the mechanical properties of cast alloys might be improved by a similar treatment. Since it would not be desirable in many cases actually to quench castings in water, owing to the possibility of their cracking, the heat treatment which was applied in all of these tests consisted of heating at 500° C. for two hours followed by cooling in air; the specimens were than allowed to age several days before testing. Such a heat treatment could readily be applied to most commercial castings of aluminum alloy. In the tables the specimens which were so treated are marked AC or

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[1] Aluminum and Its Light Alloys, *Circular No. 76*, Bureau of Standards, 1919; also in *Chemical and Metallurgical Engineering*, 1919.

[6] Wilm, *Metallurgie*, Vol. 8, p. 650 (1911).

[7] Cohn, Elektrotechnik u. Maschinengau, Vol. 31, p. 430 (1913).

FC depending on whether they were cooled in air or in the furnace after annealing.

Test specimens of about 30 heats were so treated. In all but five or six cases there was found to be an increase in tensile strength resulting from this treatment amounting to from 5 to 50 per cent of the strenth of the cast, unheat-treated bars. In those cases in which the heat treatment resulted in a decrease of strength the whole group of bars of the heat was of inferior quality, cast and heat-treated ones alike.

The effect of heat treatment on the elongation was more erratic; in the majority of cases the average elongation of the heat-treated bars was lower than that of the unheat-treated ones, but in several cases there resulted an increase in ductility. Thus in the case of heats G-7, Table III, and H-5, Table IV, the elongation of the treated bars was approximately 20 per cent less than that of the unheat-treated ones, while in the case of heat E-27, Table V, the elongation of the treated bars was approximately 50 per cent greater.

The presence of magnesium seems in general to increase the amount of the hardening produced by heat treatment, at least in the amounts used in these tests. This is illustrated in the results of the tests of heats G-7 and 8, Table III, and of H-5 and 6, Table IV. This is quite in accord with the fact that the presence of magnesium in duralumin increases the amount of hardening produced by heat treatment.[8]

It was observed that during the annealing of the specimens at 500° C., those which contained magnesium became covered with a dark gray coating of oxide, whereas those containing no magnesium remained quite bright and unaltered superficially during this treatment.

It would seem that the application to light aluminum castings of heat treatment of a type similar to that described above has commercial possibilities, inasmuch as it is possible in this manner to obtain high values of tensile strength and hardness in alloys containing only from 3 to 4 per cent of hardener, which still have a considerable ductility.

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[8] Merica, Waltenberg and Scott, "The Heat Treatment and Constitution of Duralumin," *Scientific Paper No. 347*, Bureau of Standards, 1919; also in *Bulletin No. 150*, Am. Inst. Min. Engrs., 1919.

RELATION BETWEEN TENSILE PROPERTIES AND HARDNESS.

The structure of cast aluminum alloys is discussed below and it is shown that these alloys fracture in most cases at the grain boundaries, the strength depending thus on the adhesion at these boundaries. The hardness of the alloys depends, however, principally upon the hardness or cohesion of the grains themselves. It is therefore not surprising that the tensile strength and the hardness of cast light alloys do not bear any simple relation to each other.

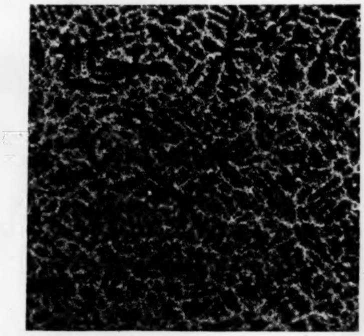

FIG. 3.—Specimen E5-M4 (×20).

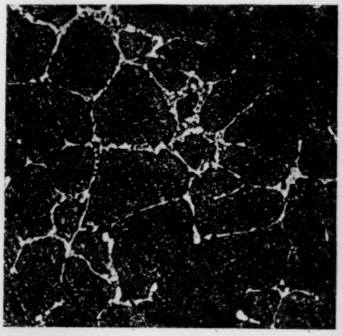

FIG. 4.—Specimen E5-M4 (×100).

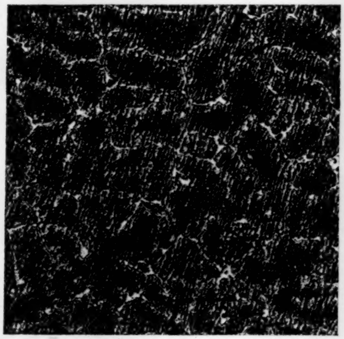

FIG. 5.—Specimen E6-M7 (×50).

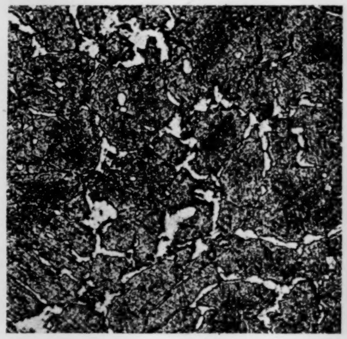

FIG. 6.—Specimen E7-M11 (×50).

The Structure of the Alloy containing 8 per cent of Copper. All Specimens Etched with 0.1 per cent NaOH.

Thus the alloys of Table II, containing about 8 per cent of copper, have an average Brinell hardness of about 65, a scleroscope hardness of about 20, together with an average tensile strength of about 19,000 lb. per sq. in. The alloys of the G-1 and G-2 series, Table III, have about the same average tensile strength, but their Brinell hardness is only about 50 and their scleroscope hardness, about 11. Again the tensile strength of the bars of heat H-5, Table IV, is greater than the average tensile strength of the 8-per-cent copper alloy, but their hardness is less.

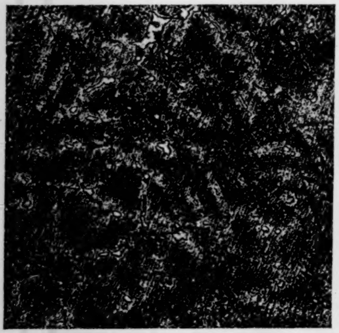

FIG. 7.—Specimen G-1-I (×50).

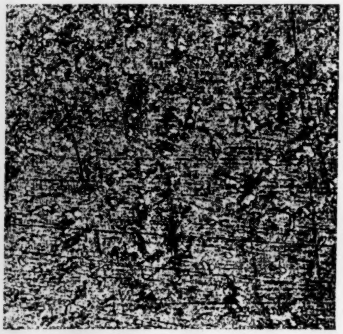

FIG. 8.—Specimen G-1-D (×50).

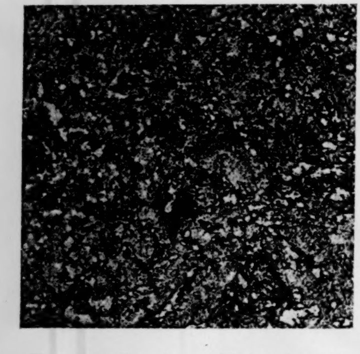

FIG. 9.—Specimen H-1-2 (×50).

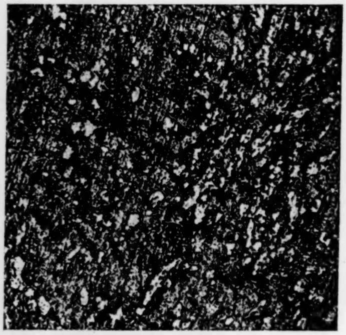

FIG. 10.—Specimen A-2-1 (×50).

Structure of Cast Alloys. All Specimens Etched with 0.1 per cent NaOH.

The effect of heat treatment is to increase both the tensile strength and the hardness, although not always in the same proportion. Thus, in Table V, the tensile strength and hardness of the specimens of C-56 were increased in about equal proportions, the tensile strength of the bars of C-20 was increased in greater proportion than the hardness, while in the case of C-44 the effect of heat treatment was to decrease the tensile strength and to increase the hardness.

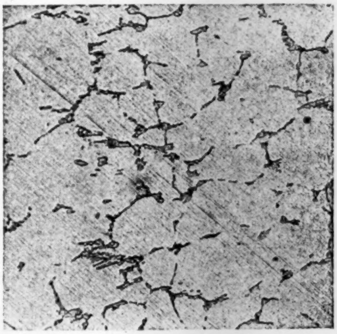

FIG. 11.—Specimen H-6-C (×100).

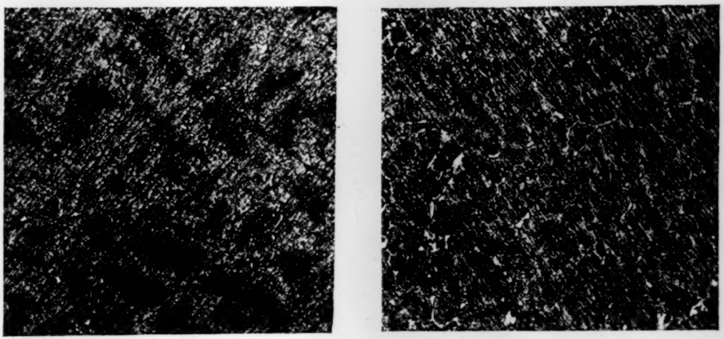

FIG. 12.—Specimen C-15-B (×50). FIG. 13.—Specimen C-19-C (×50).

Structure of Cast Alloys. All Specimens Etched with 0.1 per cent NaOH.

MICROSTRUCTURE.

Photomicrographs illustrating typical microstructures of aluminum light alloys are shown in Figs. 3 to 16; all of the alloys of which the structures are shown contain copper as the principal hardening element. Elsewhere[9] it has been shown that at 525° C. approximately 4 per cent of copper is dissolved in solid solution in aluminum as $CuAl_2$; the solubility of this compound in aluminum diminshes at lower temperatures, and is about 1 per cent at 300° C. Cast alloys containing copper therefore have a structure consisting of grains of aluminum solid solution of cored or dendritic arrangement, surrounded partially or completely by envelopes of the excess $CuAl_2$. This is illustrated in the figures.

The elements nickel and manganese also form compounds with aluminum which are only slightly soluble in aluminum and form envelopes in the same manner as does $CuAl_2$. The greater the sum of the percentages of copper, nickel and manganese the greater the volume of the compounds formed and the more complete and continuous the grain envelopes. Compare for example the structure of E-7–M-11, Fig. 6, containing 8 per cent of copper, with that of G-1–I, Fig. 7, containing 2 per cent of copper plus 1 per cent of manganese.

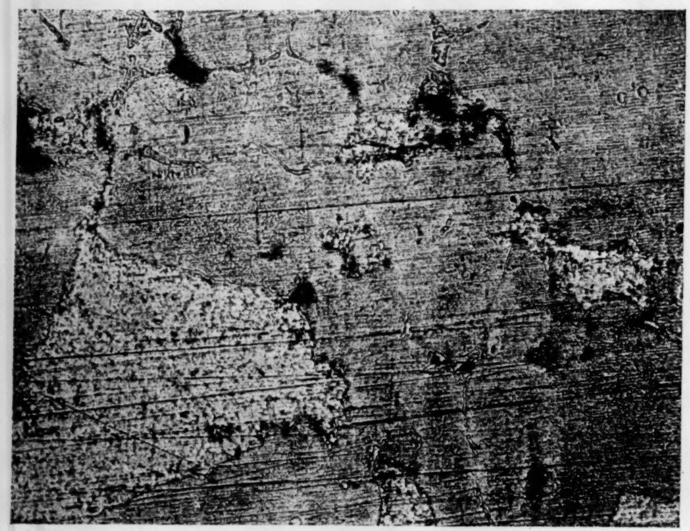

FIG. 14.—The Path of Fracture in Cast Alloys. Specimen 97 E. Etched with 0.1 per cent NaOH (×150).

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[9] Merica, Waltenberg and Freeman, "The Metallography of Aluminum and Its Light Alloys with Copper and with Magnesium, *Scientific Paper No. 337*, Bureau of Standards, 1919; also in *Bulletin No. 151*, Am. Inst. Min. Engrs., 1919.

The path of fracture in cast alloys having this structure whenever possible follows these envelopes, which are hard and brittle. This is shown in Figs. 14, 15, and 16, photomicrographs taken near or at the fractured ends of tension test specimens. When the envelopes are not complete and continuous, the fracture is forced in places to cross the grains. In Fig. 16 it is noted that the fracture occurs both at the envelopes and across the grains.

Besides increasing the volume of the envelopes of $CuAl_2$, the increase of copper content causes an increase in the average concentration of the solid solution of $CuAl_2$ in aluminum. The hardness of the alloy depends principally on the hardness of the grains, which is increased roughly in proportion to the concentration of the solid solution. Increase of copper content therefore increases the hardness of the cast alloy, and up to a certain amount, about 3 per cent, also increases the tensile strength. Beyond that amount, although the hardness continues to increase, the increase in volume of the envelopes produces a more favorable path of rupture under tensile stress, and the tensile strength is not further increased.

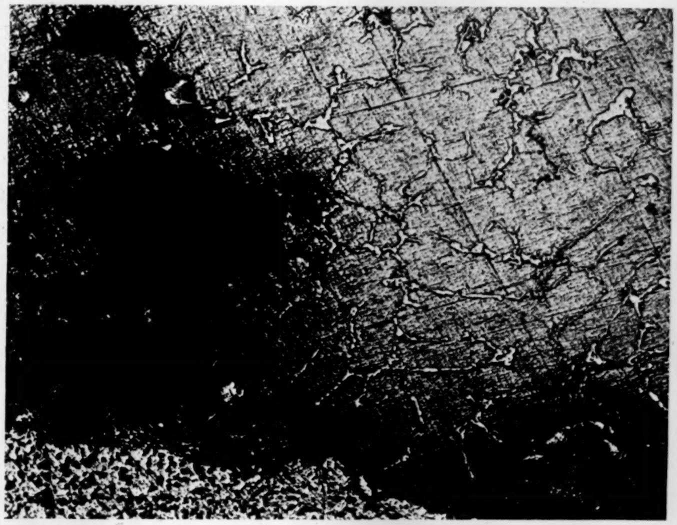

FIG. 15.—The Path of Fracture in Cast Alloys. Specimen E5-M1. Etched with 0.1 per cent NaOH (×50).

The ductility of the alloys depends on the relation between the tensile strength and the stress necessary to produce permanent deformation. If the former appreciably exceeds the latter the alloy will exhibit ductility, otherwise it will not. Within a structure such as that shown in Fig. 6, consisting of grains completely surrounded by the brittle envelopes, fracture at the envelopes occurs before the stress can be increased sufficiently to produce deformation. In a structure such as that of Figs. 9 and 10, the envelopes are broken up and discontinuous; the path of fracture is forced at least partially across the grains, and deformation within the grains can be produced before fracture occurs. The alloy of Fig. 6 exhibits practically no ductility; those of Figs. 9 and 10, from 4 to 6 per cent elongation.

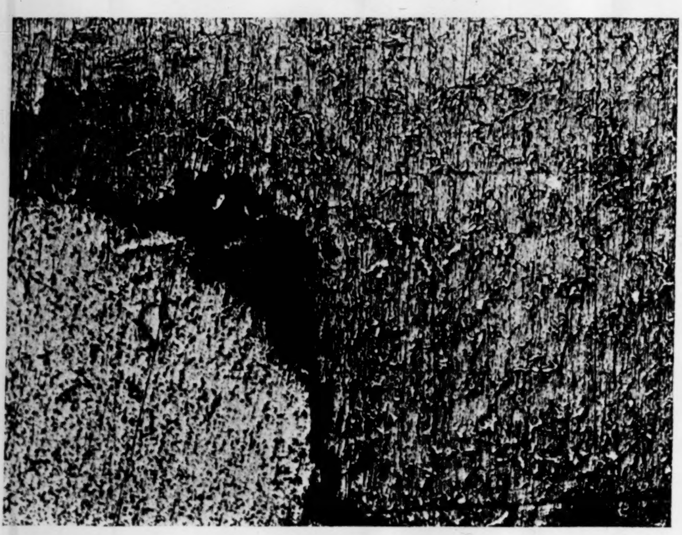

FIG. 16.—The Path of Fracture in Cast Alloys. Specimen H2-4. Etched with 0.1 per cent NaOH (×50).

RESISTANCE TO CORROSION IN THE SALT SPRAY TEST.

The resistance of these alloys to corrosion was determined by use of the salt spray test. This test consists of exposing the samples to a continuous fog of salt water, produced by atomizing a 20-per-cent solution of salt (sodium chloride) in water.[10] Although this test is not considered as entirely satisfactory, it is thought that the results produced represent with a fair degree of accuracy the results obtained in actual service, especially under marine conditions.

The alloys were subjected to the salt spray test for two periods of one month each, and were examined at the end of each period to determine the relative amount of corrosion. This was estimated by appearance only, as it is practically impossible to determine it by loss in weight on account of the adherence of the products of corrosion and the lack of a satisfactory reagent to remove the rust without affecting the metallic aluminum.

The alloys were cast $\frac{1}{4}$ in. thick; about $\frac{1}{8}$ in. was then milled from one surface so that one exposed surface was as cast, and the othere was machined. The specimens were 2 in. wide and 4 in. long.

The designation of the cast alloys with their composition and treatment is as follows:

MARKED.	TREATMENT.	COMPOSITION.
A-30-A........	As cast	Al. + 5% Mg.
A-30-A-A......	Annealed 500° C.	"
CA-40-A.......	As cast	Al. + 3% Cu. + 1% Mg.
CA-40-A-A....	Annealed 500° C.	"
G-1-F.........	As cast	Al. + 2% Cu. + 1% Mn.
G-1-F-A.......	Annealed 500° C.	"
Z-31-A........	As cast	Al. + 13.5% Zn. + 3% Cu.
Z-31-A-A......	Annealed 500° C.	"
E-A...........	As cast	Al. + 8% Cu.
E-A-A.........	Annealed 500° C.	"

These cast alloys appeared very slightly and about equally corroded after two months exposure to the salt spray, the alloy containing 5 per cent magnesium (A-30-A, and A-30-A-A) appeared somewhat better than the others. No difference could be detected between the milled surface and the surface as cast, or between the specimen as cast and annealed.

The authors are indebted to Mr. A. N. Finn for his assistance in carrying out the salt spray tests.

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[10] A. N. Finn, "Method of Making Salt Spray Test," *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part I, p. 237 (1918).

TABLE VI.—THE MECHANICAL PROPERTIES OF CAST COPPER-ZINC AND OF MAGNESIUM ALLOYS.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
A-30—C	....	5.0	....	....	....	....	700	No. 3	....	19 300	4 000	......	2.0	....	17	64
D	....	....	....	....	....	....	"	"	....	20 700	4 000	......	4.0	....	14	65
Z —1	2.3	0.5	....	....	Zn...4.1	....	....	No. 4	....	25 500	......	......	1.5	....	19	65
Z-14—E	2.9	....	....	....	Zn..12.7	750	700	......	AC	37 300	......	6 900	5.5	9.9	....	....
F	....	....	....	....	....	"	"	......	....	......	......	......	....	....	....	....
Z-15—E	3.0	....	....	....	Zn...8.4	750	700	No. 6	....	26 600	......	7 500	5.5	6.0	12	54
H	....	....	....	....	....	"	"	"	....	26 000	......	6 000	5.0	6.9	12	52
F	....	....	....	....	....	"	"	"	AC	28 600	......	5 000	8.0	7.5	10	50
G	....	....	....	....	....	"	"	"	"	29 100	......	7 500	8.0	7.5	10	50
Z-16—E	3.0	....	....	....	Zn..15.9	....	....	No. 5	....	35 100	......	14 000	2.0	2.0	15	74
F	....	....	....	....	....	....	....	"	AC	41 200	......	14 000	4.0	4.0	15	70
Z-31—C	3.2	....	....	....	Zn..13.7	....	700	No. 3	....	22 800	3 250	......	3.0	....	20	68
D	....	....	....	....	....	....	"	"	....	23 000	3 400	......	2.0	....	20	71

[1] AC indicates that the specimen was annealed for 2 hours at 500° C. and cooled in air.

TABLE VII.—THE MECHANICAL PROPERTIES OF SOME MISCELLANEOUS CAST ALLOYS.

Heat and Number.	Chemical Composition, per cent.					Temperature, deg. C.		Type of Test Bar.	Heat Treatment.[1]	Tensile Properties.					Hardness.	
	Copper.	Magnesium.	Manganese.	Nickel.	Other Metals.	Maximum Temperature During Pouring.	Pouring Temperature.			Tensile Strength, lb. per sq. in.	Yield Point (1), lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Scleroscope (Magnifier Hammer).	Brinell (500 kg.).
XE— 9	2.3	0.6	0.2	0.3	Fn...0.9	....	....	No. 5	AC	28 500	......	11 000	2.3	4.0	19	70
10	....	....	....	....	....	....	....	"	....	23 200	......	......	2.3	....	14	61
X—1	....	....	....	....	....	....	700	No. 5	AC	21 700	......	7 000	....	1.6	22	74
2	....	....	....	....	....	....	"	"	....	26 700	......	4 500	2.3	3.6	19	67
XE—1	....	....	....	....	....	....	....	No. 5	....	......	......	......	....	....	....	....
2	....	....	....	....	....	....	....	"	....	......	......	......	....	....	....	....
XE—3	....	....	....	....	....	....	700	No. 5	....	26 600	......	9 500	2.3	2.6	25	72
4	....	....	....	....	....	....	"	"	AC	25 400	......	4 500	2.5	4.1	20	75
XE—5	....	....	....	....	....	....	700	No. 5	AC	25 600	......	......	3.9	6.6	17	61
6	....	....	....	....	....	....	"	"	....	17 100	......	......	3.9	1.5	13	48
XE—7	....	....	....	....	....	....	700	No. 5	AC	30 400	......	12 000	1.6	4.5	19	71
8	....	....	....	....	....	....	"	"	....	15 200	......	......	....	....	15	66

[1] AC indicates that the specimen was annealed for 2 hours at 500° C. and cooled in air.

RESISTANCE TO THE ACTION OF ALTERNATING STRESSES.

Light aluminum casting alloys are called upon not only to resist the action of a constant load or stress but also frequently to resist vibratory stresses, as for example, in a crank case. There is little published information on the subject of the resistance of light alloys to the action of alternating stresses. Elmendorf[1] finds that cast commercial aluminum subjected to the White-Souther test will withstand 1,000,000 reversals of stress at a maximum fiber stress of 10,000 lb. per sq. in.

Jeffries[2] states that the cast alloy containing 8 per cent of copper will withstand an unlimited number of alternations of tensile stress between zero and 12,000 lb. per sq. in.

Three compositions of alloy were tested in this respect: that containing 8 per cent of copper (the E series), that containing from 2 to 3 per cent of copper and from 12 to 15 per cent of zinc (the Z series), and that containing from 1.5 to 2 per cent of copper and from 1.5 to 2 per cent of manganese (the G series). The test bars were cast horizontal in green sand, with gate and riser, each being 27 in. long and $\frac{7}{8}$ in. in diameter. The bars were machined for test to a uniform diameter of 0.740 in.

A modification of the old Wöhler or White-Souther machine was used for the testing. Each bar was supported at the two outside points and the load applied at the two intermediate third points by means of weights in the usual manner. These points were 8 in. apart. The specimens were then rotated at an approximately uniform rate of 1000 r. p. m., the number of rotations to rupture being indicated in the usual manner with a revolution counter.

The results of the tests are given in Table VIII and in the curves of Fig. 17. For comparison the tensile properties determined on the usual type of tension test bar, of the heats from which alternating stress test bars were poured and tested, may be seen in Tables II, III, and VI.

There seems to be no marked difference between the different compositions as regards their resistance to alternating stresses. The series E seems to be somewhat superior to the others, the

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[1] A. Elmendorf, Tables and Charts resulting from the Testing of Cast Aluminum on a White-Souther Rotary Testing Machine, *American Machinist*, Vol. 41, p. 811 (1914).

[2] "Aluminum and Its Light Alloys," *Circular No. 76*, Bureau of Standards, 1919; also in *Chemical and Metallurgical Engineering*, 1919.

TABLE VIII.—THE RESISTANCE TO ALTERNATING STRESSES OF CAST ALLOYS OF SERIES E, G, AND Z.

ALLOYS CONTAINING 8 PER CENT OF COPPER (SERIES E).

Number.	Load, lb.	Extreme Fiber Stress, lb. per sq. in.	Number of Alternations to Rupture.	Average Number of Alternations to Rupture for Each Stress.
E-8—5..........	35	7 000	103 251 000	103 251 000
E-8—3..........	40	8 000	2 559 000	6 650 000
10..........	"	"	12 394 000	....
E-21—A.........	"	"	5 145 000	....
E-8—7..........	45	9 000	16 895 000	16 895 000
E-8—1..........	50	10 000	1 522 000	1 940 000
2..........	"	"	2 368 000	....
E-8—4..........	55	11 000	715 000	980 000
11..........	"	"	1 248 000	....
E-8—6..........	60	12 000	945 000	570 000
E-21—B.........	"	"	196 000	....

ALLOYS CONTAINING: COPPER........1.5–2 per cent.
MANGANESE....1.5–2 " (Series G).

G-3—1..........	25	5 000	37 545 000	37 545 000
G-3—4..........	35	7 000	17 123 000	12 680 000
6..........	"	"	28 170 000	....
7..........	"	"	12 929 000	....
G-12—A.........	"	"	4 101 000	....
B.........	"	"	8 802 000	....
C.........	"	"	4 962 000	....
G-3—3..........	40	8 000	880 000	1 390 000
5..........	"	"	1 911 000	....
G-3—2..........	45	9 000	896 000	1 210 000
8..........	"	"	1 846 000	....
G-11—3.........	"	"	1 349 000	....
A..........	"	"	740 000	....
G-3—10.........	50	10 000	1 305 000	720 000
11..........	"	"	1 149 000	....
G-10—A.........	"	"	422 000	....
D..........	"	"	310 000	....
G-11—2..........	"	"	428 000	....

ALLOYS CONTAINING: COPPER........ 2–3 per cent.
ZINC...........12–15 " (Series Z).

Z-14—C.........	30	6 000	67 790 000	67 790 000
Z-16—B.........	35	7 000	5 177 000	5 177 000
Z-14—B.........	40	8 000	3 651 000	3 820 000
D.........	"	"	3 655 000	....
Z-16—C.........	"	"	4 145 000	....
Z-14—A.........	45	9 000	2 826 000	2 826 000
Z-16—A.........	50	10 000	1 377 000	1 377 000
D.........	55	11 000	618 000	618 000

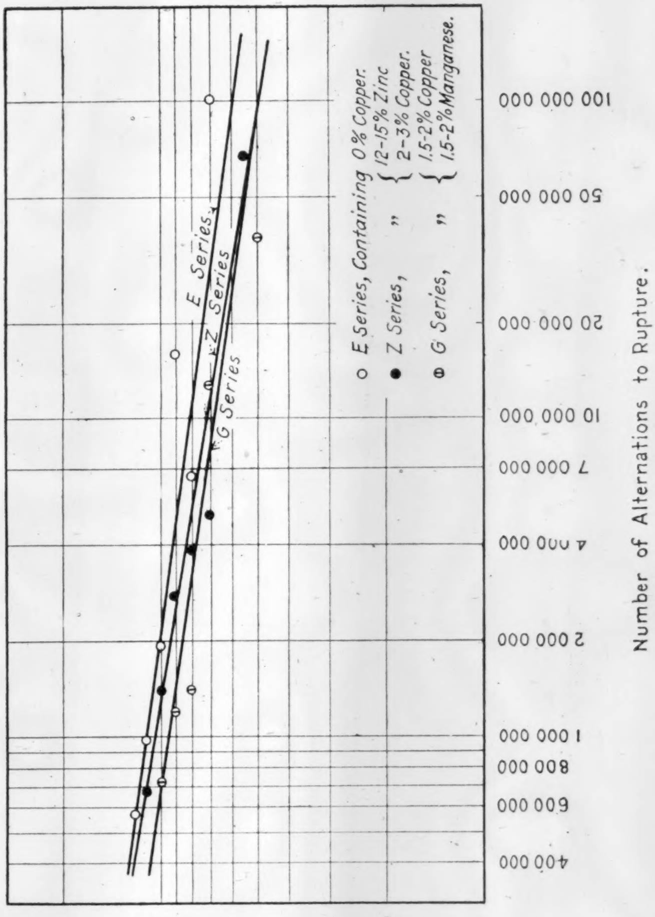

FIG. 17.—The Resistance of Cast Aluminum Alloys to the Action of Alternating Stresses.

series G slightly inferior. The curves in Fig. 17 are drawn through the mean of the mean number of alternations to rupture for each stress. The following values are taken from the three curves:

			SERIES.		
			E	Z	G
Maximum fiber stress withstood at	1,000,000	alternations	11,000	10,400	9,500
" " " " "	10,000,000	"	8,200	7,200	6,900
" " " " "	100,000,000	"	6,000	5,000	5,000

These results are apparently best expressed in the form of curves or in such a table, but the following equations of the usual type are calculated from the mean curves:

For the E series............$S=68,000\ N^{-0.132}$
For the Z series............$S=93,000\ N^{-0.159}$
For the G series............$S=65,000\ N^{-0.139}$

where S = the maximum fiber stress in pounds per square inch, and N = number of alternations to rupture.

These equations may be compared with that given by Elmendorf:[1]

$$S=48,000\ N^{-0.113}$$

for cast commercial aluminum. It appears that the resistance to the action of alternating stresses does not increase in proportion as the tensile strength or the hardness of the alloy increases. Thus according to Elmendorf aluminum alone will withstand as many alternations of stress at fiber stresses of from 7,000 to 10,000 lb. per sq. in. as will the alloy G, which has a tensile strength from 20 to 50 per cent higher than that of the aluminum.

The authors are indebted to Mr. L. J. Larson for his assistance in carrying out the above tests.

SUMMARY AND CONCLUSIONS.

The tensile properties and the hardness of a number of different compositions of light aluminum casting alloys have been determined; the resistance to corrosion compared and the resistance to the action of alternating or vibratory stresses determined of a few commonly used compositions.

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[1] *Loc. cit.*

It is advisable to use for tension tests a test bar cast almost to size; a bar cast with the test length $\frac{9}{16}$ in. in diameter, afterwards machined to 0.505 in., gives satisfactory results. The use of a type of test specimen which can be gripped in a self-centering holder in the testing machine is recommended.

A study of the effect of chemical composition on the mechanical properties has shown that it is possible to obtain an alloy containing from 2 to 3 per cent of copper together with 1 or 2 per cent of nickel, manganese, or both, which will have a reasonable amount of ductility, and it is believed that an alloy of this type should have commercial value. Tensile properties are suggested for such an alloy. The addition of magnesium to alloys containing copper reduces in a marked manner the ductility, but increases the tensile strength and the hardness.

The effect of heat treatment on test bar castings, consisting of annealing at 500° C., cooling in air from this temperature and allowing to age for several days, is to increase the tensile strength and the hardness; the ductility of the alloy is generally decreased but may in some cases be increased. The presence of magnesium in the alloy in amounts of from 0.5 to 1.5 per cent seems to increase the hardening effect of heat treatment. The heat treatment of light aluminum castings would seem to have commercial possibilities.

The microstructure of the different alloys was studied and it was found that fracture in them prefers a path along the brittle envelopes surrounding the grains of aluminum, consisting of the various eutectics which are formed with the added metals or their compounds with aluminum.

Two months exposure in the salt spray produced only slight corrosion of several compositions of cast alloys. There was no very appreciable difference between the different compositions in resistance to corrosion.

A study of the resistance to the action of alternating stresses of three compositions of light cast alloys showed that there was no marked difference in the behaviour of the three alloys in this test, although the one series was somewhat superior and another series somewhat inferior to the others. All of the three alloys will withstand 10,000,000 complete reversals (tension to compression) at a maximum fiber stress of 7000 lb. per sq. in.

EFFECT OF FINENESS OF CEMENT.

By Duff A. Abrams.

SUMMARY.

The recent revision of the Standard Specifications for Portland Cement served to focus the attention of engineers on the function of fineness of grinding of cement in producing concrete of high strength and other desirable properties. An investigation of this subject has been under way at Lewis Institute for the past four years. Five series of tests have been completed; another series, now under way, is not included in this report. These studies were made as a part of the investigations of concrete and concrete materials being carried out through the cooperation of the Portland Cement Association and Lewis Institute at the Structural Materials Research Laboratory.

The Portland cements used were from seven commercial mills. These plants represent the principal cement-producing districts east of the Mississippi River. Fifty-one different samples of cement were used. The cements were ground at the mill to four to seven degrees of fineness, which gave residues ranging from 2 to 43 per cent on the standard No. 200 sieve. In general, the aggregate consisted of sand and pebbles; in one series blast-furnace slag and a light-weight aggregate consisting of burnt shale were used.

This report covers compression tests on 6125 6 by 12-in. concrete cylinders, 9000 compression and tension tests of mortar, and several thousand miscellaneous tests. Strength tests of concrete and mortar were made at ages of 7 days to one year.

Definite information has been secured on the effect of fineness of cement under the following conditions:

(*a*) Effect of fineness of cement on the strength of concrete;
(*b*) Quality of concrete using different cements;

(*c*) Effect of the quantity of cement used;
(*d*) Effect of consistency of the concrete;
(*e*) Effect of size and grading of the aggregate;
(*f*) Variation in the type of aggregate;
(*g*) Effect of age of concrete;
(*h*) Elongation and contraction of concrete;
(*i*) Effect of fineness of cement on workability of concrete.

The following may be stated as the principal conclusions from the tests:

1. There is no necessary relation between the strength of concrete and the fineness of the cement, if different cements are considered.

2. In general, the strength of concrete increases with the fineness of a given lot of cement, for all mixes, consistencies, gradings of the aggregate, and ages of concrete. The cements with residues lower than about 10 per cent were inclined to give erratic results in the strength tests; one lot showed an abnormal increase, and two others a pronounced decrease in strength as compared with the other tests on coarser cements in the same lot.

3. For residues higher than 10 per cent the strength of concrete varies approximately inversely as the residue on the No. 200 sieve.

4. Fine grinding of cement is more effective in increasing the strength of lean mixtures than rich ones.

5. Fine grinding of cement is more effective in increasing the strength of concrete at 7 days than at ages of 28 days to 1 year.

6. For the usual range of consistencies the effect of fineness of cement is independent of the consistency of the concrete. The rate of increase in strength with fineness is lowered for very wet mixtures.

7. Ordinary concrete mixtures at 28 days show an increase in strength of about 2 per cent for 1 per cent reduction in the residue of the cement on the No. 200 sieve. At 7 days, 3 months and 1 year the corresponding increases in strength are about 2.5, 1.7 and 1.4 per cent.

8. The decreased benefit of fine grinding of cement with the age of the concrete does not bear out accepted opinion that the coarser particles of cement do not hydrate, but indicates that

the principal result of finer grinding is to hasten the early hardening of the concrete.

9. For the richer mixtures and the consistency necessary for building construction, the fineness of the cement has no appreciable effect on the workability of concrete as determined by the "slump" test. For leaner mixtures and wetter consistencies the finer cements showed a somewhat greater "slump" than the coarser cements.

10. The normal consistency of cement is increased with fineness of grinding. About 0.1 per cent of water (in terms of the weight of the cement) must be added for each 1 per cent reduction in residue on the No. 200 sieve.

11. The time of setting of the cement is shortened with finer grinding. In some instances initial setting time with the Vicat needle was shortened to 5 to 10 minutes.

12. The unit weight of cement decreases with fineness. For the cements used in these tests the weight varied from 76 (residue of 2.4 per cent) to 108 lb. per cu. ft. (residue 43.3 per cent). For the usual range in fineness the weight is lowered about $\frac{3}{4}$ lb. per cu. ft. for each 1 per cent reduction in the residue on the No. 200 sieve.

13. In using 94 lb. per cu. ft. as a uniform basis for proportioning the cements in these tests, the actual volume of cement in a batch *of the same mix* varies about 35 per cent. If the mixtures had been proportioned in a manner that would have given a uniform *volume* of cement, the resulting concrete strength would not have been so favorable to the finer cements.

14. The fineness of cement has no appreciable effect on the yield or density of concrete.

15. Concrete of all mixes and consistencies showed expansion in damp sand or water storage and contraction in air.

16. The change in length of concrete specimens stored in air or water is independent of the fineness of the cement and the consistency of the concrete. The lean concretes are slightly less affected than the rich mixtures.

17. The type of aggregate has little or no influence on the relative effect of fineness of cement on the strength of concrete.

18. The tests included in this report show an intimate relation between the strength of the concrete and the water-

ratio of the mixture. The lower the water-ratio (so long as the concrete is plastic and the aggregate not too coarse) the higher the strength, and vice versa. This confirms the results of other concrete tests made in this Laboratory. Increasing the quantity of cement in a given mixture enables us to secure a concrete of equal workability with a lower water-ratio, hence a higher strength.

19. In ordinary concrete mixtures (say, 1:5 to 1:4, requiring 20 to 25 per cent cement, by volume) increasing the cement content by 1 per cent (to 20.2 per cent for a 1:5 mix) gives an increase in strength of about 1 per cent.

20. One per cent increase in cement is more effective in increasing the strength of concrete in lean than in rich mixtures.

21. One per cent increase in cement is somewhat more effective in increasing the early strength of concrete than at later periods.

22. The effect of increasing the quantity of cement is independent of the consistency of the concrete.

23. Tension tests of briquettes do not give a correct measure of the relative merits of different cements as determined by compression tests of mortar and concrete.

EFFECT OF FINENESS OF CEMENT.

BY DUFF A. ABRAMS

INTRODUCTION.

The recent revision of the Standard Specifications for Portland Cement focused attention on the function of the fineness of grinding of cement in producing concrete of high strength and other desirable properties. The effect of fineness of cement has been investigated by many experimenters during the past sixty years. The earliest experimental study which has come to the writer's attention is that made by John Grant, as a part of his investigation during the construction of the London Main Drainage Works. The results of these tests were published originally in the Proceedings of the Institution of Civil Engineers, 1865 and 1870. This report has since been reprinted in book form under the title of "Strength of Cement." A great many tests on the effect of fineness of cement have been carried out by German and French investigators. The principal investigations heretofore made in this country were carried out by the Bureau of Standards.

In spite of all of the experimental work which has been done on this subject, it was found by the committee engaged in the revision of the cement specifications that little or no definite information was available with reference to the effect of fineness of cement on the *strength of concrete*. Most of the published tests refer to briquettes or other small mortar specimens. In general, the published tests are inconclusive on account of the restricted scope of the investigations, or due to the narrow range in finenesses used.

ACKNOWLEDGMENT.

Acknowledgment is made to the cement manufacturers who furnished the cements; to the Chicago Gravel Co., for sand and pebble aggregate; to the Illinois Improvement and Ballast Co., Chicago, for crushed blast-furnace slag, and to the U. S. Shipping Board, Philadelphia, for burnt shale aggregate used in these tests.

SCOPE OF TESTS.

Investigations of the effect of fineness of cement have been under way at Lewis Institute for the past four years. Five independent series of tests have been completed. Another series now under way is not included in this report. The first series of tests (No. 20) was carried out in cooperation with the Sub-Committee on Strength of Committee C-1 on Cement of the American Society for Testing Materials, and the results are here presented by permission of the committee. Subsequent studies were made as a part of the investigation of concrete and concrete materials being carried out through the cooperation of the Portland Cement Association and Lewis Institute.

The cements used were from seven commercial mills, representing the principal cement-producing districts east of the Mississippi River. The samples were ground at the mill to four to seven degrees of fineness which gave residues ranging from 2 to 43 per cent on the standard No. 200 sieve. Fifty-one different samples of cement were used. In general, the aggregate consisted of sand and pebbles; in one series blast-furnace slag and a light-weight aggregate consisting of burnt shale were used.

This report covers the following tests:

Concrete	
Compression tests of 6 by 12-in. cylinders	6125
Cement and Mortar	
Compression tests of 2 by 4-in. cylinders	4935
Tension tests of briquettes	4065
Miscellaneous tests of cement and aggregate	800
Chemical analysis of cement	100
"Slump" tests for consistency of concrete	2300
Modulus of elasticity of concrete	3200

Definite information has been secured on the effect of fineness of cement under the following conditions:

(*a*) Effect of fineness of cement on the strength of concrete (Residue 2 to 43 per cent on No. 200 sieve);

(*b*) Quality of concrete using different cements (51 samples from 7 different mills);

(*c*) Effect of the quantity of cement used (Mixes from 1:10 to neat cement);

(*d*) Effect of consistency of the concrete (Relative consistency 0.90 to 2.00);

(*e*) Effect of size and grading of the aggregate (No. 0–28 sand to 0–1½ in. aggregate);

(*f*) Variation in the type of aggregate (Sand and pebbles, blast furnace slag and burnt shale);

(*g*) Effect of age of concrete (7 days to 1 year);

(*h*) Elongation and contraction of concrete (Different mixes and consistencies for water and air storage up to 4 months);

(*i*) Effect of fineness of cement on workability of concrete.

The results of the modulus of elasticity tests are not included in this report.

OUTLINES OF TEST SERIES.

Skeleton outlines of the tests of each of the series (Tables I to III) give the principal characteristics of the cements and indicate the variations in mix, consistency, size and grading of aggregate, etc. The series numbers furnish a convenient method of reference in identifying the tests.

Series 20 was begun in August, 1915. Five different cements were used, each ground to four different degrees of fineness varying from about 10 to 33 per cent residue on the No. 200 sieve. Two concrete mixtures were used and three mortar mixtures. Tests were made at ages of 7 days to 1 year.

Series 31, an outgrowth of the tests in Series 20, was begun March, 1916. It was felt that a sufficient number of finenesses was not used in Series 20, consequently in Series 31 two cements were ground to seven different degrees of fineness, and one to five degrees; the fineness varied from about 2 to 34 per cent residue. In this series greater emphasis was placed on the concrete than on the mortar tests. Five different concrete mixtures were used and two mortar mixtures. Tests were made for all conditions at ages of 7 days to 1 year.

Series 60 (October, 1916) was outlined for the purpose of determining the effect of fineness of cement on the strength of mortars made of sands of different grading. Six different gradings were made up using sand from Elgin, Ill., each graded to No. 4 sieve. Compression tests were made on 2 by 4-in. cylinders using Cement F from Series 31, ground to seven different degrees of fineness.

Series 118 (November, 1918) was carried out primarily for the purpose of studying the effect of fineness of cement using concretes of rich mixtures and different consistencies. Two of the cements were ground to five degrees of fineness. For the third cement (I) only two degrees of fineness were available.

TABLE I.—OUTLINES OF TESTS—SERIES 20, 31 AND 60.

Tension tests of briquettes and compression tests of 2 by 4-in. and 6 by 12-in. cylinders.
Mortar specimens mixed 5 in a batch, 1 for each age.
Concrete specimens proportioned and mixed in separate batches.
Mortar specimens stored in water; tested damp.
Concrete specimens stored in damp sand; tested damp.
Normal consistency mixtures.

Fineness of Cement Residue on No. 200 Sieve.	Form of Specimen.	Mix.	Aggregate.			Age at Test.	Specimens in a Set.	Number of Specimens.
			Kind.	Size.	F. M.			
			SERIES 20.					
A B C D E 12.5 12.1 16.1 16.1 10.6 16.9 16.5 20.6 20.3 15.3 19.9 20.4 26.5 22.3 18.9 22.9 23.0 33.3 25.6 23.7	Briquettes 2 by 4-in. Cylinders.	Neat[1] 1:2 1:3 1:4	Standard sand Elgin sand	No. 20–30 0–No. 4	2.67 3.00	7 d. 28 d. 3 mo. 6 mo. 1 yr.	4	**3900**
	6 by 12-in. Cylinders.	1:2:4 1:3:5	Elgin sand and pebbles	0–1¼ in.	5.60 5.43			**600**
			SERIES 31.					
F G H 4.9 2.2 12.0 8.7 7.9 19.9 14.2 12.9 23.3 17.9 19.9 25.1 24.5 25.2 30.1 28.1 29.6 .... 33.4 34.0	Briquettes 2 by 4-in. Cylinders.	Neat[1] 1:3	Standard sand Elgin sand	No. 20–30 0–No. 4	2.67 3.00	7 d. 28 d. 3 mo. 6 mo. 1 yr.	4	**2650**
	6 by 12-in. Cylinders.	1:1½:3 1:1¾:3½ 1:2:4 1:2½:5 1:3:6	Elgin sand and pebbles	0–1¼ in.	5.53			**2375**
			SERIES 60.					
F 4.9 8.7 14.2 17.9 24.5 28.1 33.4	2 by 4-in. Cylinders.	1:2.55 Elgin sand by volume.		0–No. 4 0–No. 4 0–No. 4 0–No. 4 0–No. 8 0–No. 4	4.44 4.06 3.63 3.17 3.00 2.53	7 d. 28 d. 3 mo. 6 mo. 1 yr.	5	**1050**

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[1] Briquettes only.

Cements I differed from the others in that they were not prepared from the same lot of clinker. Cement I-1 was used in the reinforced concrete ship "Atlantus" constructed at Brunswick, Ga. The samples were furnished by the U. S. Shipping Board for use in these tests. I-2 was the commercial product of the same brand, purchased from a contractor in Brunswick. In this series the aggregate was of small size, the purpose being to use the same mixture and aggregate of the size employed in

TABLE II.—OUTLINE OF TESTS—SERIES 118.

Compression tests of 6 by 12-in. concrete cylinders. Hand-mixed concrete.
Concrete for each cylinder proportioned and mixed in a separate batch.
Plasticity determined by the "slump" method.
Five tests in a set made on different days.
Stored in damp sand; tested at 28 days.
Cement I-1, same as that used in concrete ship "Atlantus."
Cement I-2, standard mill product purchased from local contractor, Brunswick, Ga.
Cements K and L, different brands ground to 5 degrees of fineness.

Ref. No.	Cement.		Mix by Volume.	Relative Consistency.	Aggregate.		Number of Tests.
	Fineness, Residue on No. 200 Sieve.[1]	Normal Consistency.			Kind.	Grading.	
I-1...	8.9	23.5	1:1¾	0.90 1.00 1.05 1.10 1.15 1.20 1.25 1.50	Shale slag, sand and celite (*Same aggregate* and proportions as in concrete ship "Atlantus.")	0–⅜ in.	48
I-2...	13.9	22.8					
K-1...	2.4	25.0	1:4	0.95 1.00 1.05 1.10 1.15 1.20 1.25 1.50 2.00	Elgin sand and pebbles.	0–¾ in.	225
K-2...	9.4	23.4					
K-3...	17.7	23.0					
K-4...	27.9	22.8					
K-5...	36.2	22.2					
K-1...	2.4	25.0	1:1¾	0.95 1.00 1.05 1.10 1.15 1.20 1.25 1.50 2.00	Crushed blast-furnace slag, sand and celite. (Grading of aggregate and mix, same as in concrete ship "Atlantus.")	0–⅜ in.	360
K-2...	9.4	23.4					
K-3...	17.7	23.0					
K-4...	27.9	22.8					
K-5...	36.2	22.2					
L-1...	7.1	23.4					
L-2...	16.3	22.9					
L-3...	28.9	21.8					
L-4...	32.3	21.4					
L-5...	43.3	20.0					

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[1] Values for cement K are the average of 15 to 18 tests; cement L, 5 to 7 tests, and for cement I, 3 tests. In these tests 3 to 5 different standard sieves were used.

reinforced concrete ship construction. The burnt shale aggregates were the same as that used in the ship "Atlantus." The coarse aggregate in this case consisted of burnt shale which, after crushing, was graded in size up to about ⅜ in. Small quantities of "celite" and fine sand were also used in the mixture. In another group in this series the mixtures and grading of

TABLE III.—OUTLINE OF TESTS—SERIES 120.

Compression tests of 6 by 12-in. concrete cylinders. Hand-mixed concrete.
Concrete for each cylinder proportioned and mixed in a separate batch.
Cements ground at the mill to 5 different degrees of fineness.
Aggregate, sand and pebbles from the Elgin, Ill., pit of the Chicago Gravel Co.
Plasticity measured by the "slump" method.
Stored in damp sand; tested damp.
Cylinders in a set mixed on different days.

Ref. No.	Cement.		Mix by Volume.	Size of Aggregate.	Relative Consistency.	Age at Test.	Cylinders in Set.	Total Cylinders.
	Fineness, Residue on No. 200 Sieve.[1]	Normal Consistency.						
K-1...	2.4	25.0	1:10 1:7 1:5 1:4 1:3 1:2	0–1½ in.	0.90 1.00 1.10 1.25 1.50 2.00	28 d.	6[a]	1080
K-2...	9.4	23.4						
K-3...	17.7	23.0						
K-4...	27.9	22.8						
K-5...	36.2	22.2						
K-1...	2.4	25.0	1:4	0–1½ in.	0.90 1.00 1.10 1.25 1.50 2.00	7 d. 3 mo. 1 yr.	5	450
K-2...	9.4	23.4						
K-3...	17.7	23.0						
K-4...	27.9	22.8						
K-5...	36.2	22.2						
K-1...	2.4	25.0	1:4	0–No. 28 0–No. 14 0–No. 8 0–No. 4 0– ⅜ in. 0– ¾ " 0–1½ "	1.10	7 d. 28 d. 3 mo. 1 yr.	5	700
K-2...	9.4	23.4						
K-3...	17.7	23.0						
K-4...	27.9	22.8						
K-5...	36.2	22.2						
K-1...	2.4	25.0	1:4	0–No. 28 0–No. 14 0–No. 8 0–No. 4 0– ⅜ in. 0– ¾ " 0–1½ "	1.10	Elongation and Contraction tests only	1	35
K-2...	9.4	23.4						
K-3...	17.7	23.0						
K-4...	27.9	22.8						
K-5...	36.2	22.2						
L-1....	7.1	23.4	1:10 1:7 1:5 1:4 1:3 1:2	0–1½ in.	0.90 1.00 1.10 1.25 1.50 2.00	28 d.	3	540
L-2...	16.3	22.9						
L-3...	28.9	21.8						
L-4...	32.3	21.4						
L-5...	43.3	20.0						

[1] Values for cement K are the average of 15 to 18 tests; for cement L, 5 to 7 tests. In these tests 3 to 5 different standard sieves were used.

[a] Measurements of elongation and contraction only, on one round.

TABLE IV.—MISCELLANEOUS TESTS OF CEMENTS.

Cement Ref. No.	Fineness, Residue on Sieve No.		Per Cent Flour.[1]	Weight, lb. per cu. ft.	Normal Consistency, per cent by Weight.	Time of Setting.				Soundness Test (Over boiling water).
						Vicat Needle.		Gillmore Needle.		
	100	200				Initial. h m	Final. h m	Initial. h m	Final. h m	
					SERIES 20.					
A-1	1.7	12.5	35.5	....	23.0	1-15	5-00	3-00	6-00	O K
A-2	2.8	16.9	32.6	....	23.0	2-15	6-00	3-00	6-30	"
A-3	3.6	19.9	30.3	....	22.5	2-30	7-00	4-00	7-30	"
A-4	4.3	22.9	29.3	....	22.0	2-15	7-30	3-45	7-30	"
B-1	1.5	12.1	37.4	....	23.0	1-15	4-00	2-50	4-45	"
B-2	2.2	16.5	33.8	....	23.0	1-15	4-00	3-00	5-00	"
B-3	3.5	20.4	32.3	....	23.0	1-45	4-45	3-15	6-00	"
B-4	4.5	23.0	30.4	....	23.0	1-45	5-00	3-15	6-00	"
C-1	2.8	16.1	30.5	....	21.0	2-15	6-00	3-00	6-00	"
C-2	4.7	20.6	31.1	....	20.0	1-45	5-00	2-50	5-00	"
C-3	9.3	26.5	29.1	....	19.5	1-50	5-00	3-00	5-00	"
C-4	13.3	33.3	....	....	19.0	2-35	6-00	3-00	6-00	"
D-1	1.8	16.1	33.9	....	22.5	4-30	8-45	5-30	8-45	"
D-2	2.4	20.3	29.1	....	22.0	4-45	8-45	5-45	8-45	"
D-3	4.1	22.3	30.9	....	21.5	4-00	8-45	5-00	8-45	"
D-4	5.0	25.6	27.8	....	21.0	4-00	8-45	5-00	8-45	"
E-1	1.2	10.6	37.3	....	24.5	3-30	6-30	4-45	8-45	"
E-2	1.8	15.3	33.8	....	24.0	3-00	6-30	4-45	8-45	"
E-3	2.9	18.9	31.3	....	23.5	3-00	6-40	4-30	8-30	"
E-4	4.9	23.7	30.1	....	23.0	3-00	6-30	4-15	8-20	"
					SERIES 31.					
F-1	1.4	4.9	....	....	29.0	0- 5	3-45	2-30	6-30	O K
F-2	1.3	8.7	....	....	28.0	0- 7	4-15	2-45	6-30	"
F-3	1.7	14.2	....	....	27.0	0-20	6-20	3-30	7-15	"
F-4	2.7	17.9	....	....	26.0	0-17	7-00	4-30	8-00	"
F-5	5.2	24.5	....	....	25.0	0-15	6-30	4-30	8-00	"
F-6	7.5	28.1	....	....	24.5	0-15	6-30	4-15	8-00	"
F-7	11.6	33.4	....	....	24.0	2-00	7-15	4-30	7-45	"
G-1	0.8	2.2	....	....	29.0	0-25	3-45	2-15	4-30	"
G-2	0.9	7.9	....	....	26.0	2-45	4-00	4-00	5-30	"
G-3	1.2	12.9	....	....	25.0	4-00	7-15	4-30	7-45	"
G-4	2.7	19.9	....	....	25.0	0-50	9-00	6-00	9-45	"
G-5	5.8	25.2	....	....	24.5	4-30	8-45	6-00	9-00	"
G-6	6.8	29.6	....	....	24.5	5-45	9-30	6-30	9-30	"
G-7	11.0	34.0	....	....	24.0	4-15	9-45	5-20	9-45	"
H-1	1.9	12.0	....	....	23.0	1-40	5-00	3-00	6-15	"
H-2	3.3	19.9	....	....	23.0	2-10	5-45	3-45	7-15	"
H-3	4.7	23.3	....	....	21.5	1-45	5-45	3-10	6-15	"
H-4	5.9	25.1	....	....	22.0	2-45	6-15	3-45	7-00	"
H-5	10.9	30.1	....	....	22.0	3-10	7-00	4-15	7-30	"
					SERIES 60.					
F-1	1.4	4.9	....	....	26.0	1-25	4-35	3-20	5-25	O K
F-2	1.3	8.7	....	....	26.0	1-20	5-20	2-55	5-45	"
F-3	1.7	14.2	....	....	24.5	2-20	6-15	4-00	7-40	"
F-4	2.7	17.9	....	....	24.0	1-10	8-15	3-40	10-30	"
F-5	5.2	24.5	....	....	23.0	2-40	7-05	4-05	8-20	"
F-6	7.5	28.1	....	....	22.0	1-10	8-50	3-40	10-30	"
F-7	11.6	33.4	....	....	22.0	2-55	6-55	4-35	8-25	"

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[1] Tests made by the Bureau of Standards in accordance with the methods described in Technologic Paper No. 48 "An Air Analyzer for Determining the Fineness of Cement." See Table V for results of air analyzer tests made in this Laboratory.

TABLE IV—*Continued.*

Cement Ref. No.	Fineness, Residue on Sieve No.		Per Cent Flour.	Weight, lb. per cu. ft.	Normal Consistency, per cent by Weight.	Time of Setting.				Soundness Test (Over boiling water).
	100	200				Vicat Needle.		Gillmore Needle.		
						Initial. n m	Final. h m	Initial. h m	Final. h m	
SERIES 118 AND 120.										
I-1	....	8.9	....	90	23.5	5–45	11–20	6–25	12–00	O K
I-2	....	13.9	....	95	22.8	6–20	12–00	7–40	13–05	"
K-1	....	2.4	....	76	25.1	0–30	4–45	4–30	6–45	"
K-2	....	9.4	....	84	23.4	3–50	6–50	5–20	11–05	"
K-3	....	17.7	....	91	23.0	5–00	11–45	5–55	13–15	"
K-4	....	27.9	....	100	22.8	6–15	12–25	7–25	13–30	"
K-5	....	36.2	....	104	22.2	5–55	13–15	6–40	14–10	"
L-1	....	7.1	....	82	23.4	4–25	12–20	6–45	14–10	"
L-2	....	16.3	....	91	22.9	4–50	12–45	7–00	13–50	"
L-3	....	28.9	....	99	21.8	5–55	13–10	6–45	14–20	"
L-4	....	32.3	....	104	21.4	5–20	14–20	6–55	15–00	"
L-5	....	43.3	....	108	20.0	6–30	14–45	7–10	15–10	"

TABLE V.—MECHANICAL ANALYSES OF CEMENTS—SERIES 118–120.

Analysis of material finer than No. 200 sieve made in air analyzer (see Fig. 3).

Cement Lot No.	Amount Coarser than Each Size, per cent by Weight.						
	Air Analyzer No.				Sieve No.		
	D (0.00035)[1]	C (0.00075)	B (0.00130)	A (0.00181)	200 (0.0038)	100 (0.0066)	48 (0.0137)
K-1	73.7	44.0	22.4	14.0	2.4	0.6	0
K-2	74.7	58.9	38.5	28.9	9.4	0.5	0
K-3	79.3	65.5	46.5	38.4	17.7	2.0	0
K-4	82.5	70.8	55.0	47.6	27.9	7.6	0.4
K-5	86.3	75.6	60.7	54.8	36.2	15.2	1.5
L-1	68.7	51.1	34.2	25.5	7.1	0	0
L-2	75.5	60.5	42.8	34.2	16.3	0.9	0
L-3	84.2	72.1	56.0	49.8	28.9	12.1	3.2
L-4	85.2	74.3	58.7	52.0	32 3	13.8	4.4
L-5	86.8	76.5	63.3	58.2	43.3	26.1	12.4

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[1] Separation size in inches. The separation size is the diameter of the sphere having a volume equal to the volume of the last particles passing the sieve or discharged by the air analyzer Separation size $=\sqrt[3]{L\times M\times S}$, where L, M and S are the three dimensions of the particles. These dimensions were determined by microscopic measurements on a large number of particles. In making these measurements we followed the methods developed by the Bureau of Standards and described in their Technologic Paper No. 48. Due to the elongated shape of the last particles passing the sieves the separation size is larger than the clear opening of sieve; for example, the clear opening of the standard No. 200 sieve is 0.0029 in.

TABLE VI.—CHEMICAL ANALYSIS OF CEMENTS.

Cement Ref. No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CO_2	Insoluble Residue.	Loss on Ignition.
SERIES 20.									
A-1	21.12	7.20	1.88	63.41	2.03	1.53	0.75	0.30	2.34
A-2	21.32	7.34	1.85	63.45	1.93	1.45	0.38	0.25	2.15
A-3	21.32	7.30	1.85	63.73	1.95	1.33	0.30	0.18	1.83
A-4	21.38	7.31	1.85	63.30	1.92	1.47	0.31	0.18	2.09
B-1	19.58	7.31	2.75	63.38	1.54	1.43	0.95	0.20	3.92
B-2	19.72	7.33	2.75	63.80	1.67	1.37	0.73	0.20	3.24
B-3	19.94	7.29	2.85	63.24	1.68	1.35	0.98	0.20	3.52
B-4	19.74	7.51	2.70	64.08	1.59	1.30	0.73	0.17	2.99
C-1	22.04	5.41	2.10	63.10	2.88	1.85	0.71	0.15	2.10
C-2	22.30	5.35	2.03	63.10	2.99	1.55	0.58	0.30	2.03
C-3	22.08	5.52	2.20	63.03	2.92	1.65	0.60	0.30	2.20
C-4	22.04	5.85	2.01	62.96	2.95	1.64	0.69	0.22	2.01
D-1	21.60	6.76	2.80	62.45	1.90	1.26	0.98	0.19	2.43
D-2	21.64	6.81	2.95	62.72	1.76	1.82	0.37	0.25	1.90
D-3	21.76	7.04	2.90	62.52	1.79	1.63	0.40	0.19	1.96
D-4	21.94	6.44	2.80	63.01	1.95	1.32	0.34	0.25	1.55
E-1	19.76	8.15	3.75	63.12	1.02	2.03	0.42	0.45	1.48
E-2	19.76	8.03	3.75	63.33	1.04	1.96	0.32	0.41	1.55
E-3	19.54	7.97	3.75	63.82	1.09	1.89	0.45	0.37	1.60
E-4	19.56	8.11	3.75	63.40	1.09	2.01	0.42	0.32	1.46
SERIES 31 AND 60									
F-1	19.24	7.78	3.16	63.62	1.20	1.72	....	....	2.65
F-2	19.10	7.84	3.08	63.71	1.24	1.67	....	....	2.53
F-3	19.10	7.78	3.12	63.76	1.20	1.70	....	....	2.50
F-4	19.10	7.94	3.04	63.76	1.23	1.93	....	....	2.20
F-5	19.10	7.78	3.12	63.97	1.19	1.85	....	....	2.43
F-6	19.08	7.78	3.12	63.97	1.26	1.70	....	....	2.45
F-7	19.14	7.61	3.04	64.09	1.49	1.75	....	....	2.27
G-1	20.36	7.15	1.85	63.45	2.03	1.51	....	....	3.02
G-2	21.14	7.36	1.80	64.16	2.08	1.29	....	....	1.60
G-3	20.98	7.40	1.80	64.01	1.93	1.50	....	....	1.65
G-4	20.52	7.30	1.90	64.01	2.03	1.56	....	....	2.05
G-5	20.94	7.25	1.85	64.08	1.97	1.37	....	....	1.86
G-6	20.94	7.39	1.75	64.16	1.98	1.56	....	....	1.70
G-7	21.10	7.35	1.75	64.08	1.95	1.46	....	....	1.75
H-1	22.13	6.65	2.70	61.56	2.42	1.93	....	....	2.39
H-2	20.95	6.27	2.60	60.35	2.37	3.77	....	....	3.15
H-3	21.67	6.79	2.70	61.27	2.50	2.20	....	....	2.50
H-4	21.71	6.83	2.70	61.42	2.44	2.40	....	....	2.55
H-5	21.81	6.77	2.70	61.13	2.51	2.63	....	....	2.62
SERIES 118 AND 120									
I-1	21.05	10.97		62.56	1.20	1.42	1.04	0.66	2.84
I-2	22.23	10.33		62.64	0.85	1.43	1.40	0.61	3.30
K-1	19.95	10.11		62.07	2.21	1.93	0.82	0.80	3.14
K-2	19.71	10.52		63.37	2.40	1.99	0.71	0.23	1.92
K-3	19.80	11.35		62.45	2.31	2.03	1.15	0.35	2.34
K-4	20.78	11.41		61.83	2.28	2.07	3.51	0.48	1.92
K-5	20.03	8.19		64.92	1.86	2.09	0.42	0.84	2.14
L-1	22.24	9.04		62.61	2.05	1.90	0.67	0.94	2.14
L-2	21.63	9.31		62.95	1.58	1.90	0.83	0.10	2.41
L-3	22.45	8.92		63.16	2.00	1.93	0.75	0.50	2.05
L-4	22.27	9.34		63.16	1.70	1.90	0.89	0.80	2.29
L-5	22.11	9.46		62.26	2.06	1.95	0.96	0.53	3.00

NOTE.—Analysis of cements B were made after 6 months storage in laboratory; CO_2 and loss on ignition are high on this account.

TABLE VII.—MISCELLANEOUS TESTS OF AGGREGATES.

Material.	Size.	Weight, lb. per cu. ft.	Density.	Sieve Analysis. (Per cent Coarser than Each Sieve.)									Fineness Modulus.[1]
				100	48	28	14	8	4	⅜ in.	¾ in.	1½ in.	
				SERIES 20.									
Elgin sand	0–No. 4	108	0.646	98	90	68	47	24	0	..	..	..	3.27
Elgin pebbles	No. 4–1¼ in.	102	0.612	100	100	100	100	100	98	70	7	0	6.75
Elgin sand and pebbles (1:2:4 mix)	0–1¼ “	...	...	99	97	90	82	75	65	47	5	0	5.60
Elgin sand and pebbles (1:3:5 mix)	0–1¼ “	...	...	99	96	88	80	72	61	43	4	0	5.43
				SERIES 31.									
Elgin sand	0–No. 4	106	0.636	99	90	61	35	16	0	..	..	..	3.01
Elgin pebbles	No. 4–1¼ in.	104	0.623	100	100	100	100	100	100	60	20	0	6.80
Elgin sand and pebbles	0–1¼ “	...	....	99	97	87	78	72	67	40	13	0	5.53
				SERIES 60.									
Elgin sand N-14	0–No. 4	109	0.652	100	98	95	86	65	0	..	..	..	**4.44**
“ “ N-10	0–No. 4	112	0.670	99	94	88	75	50	0	..	..	..	4.06
“ “ N-7	0–No. 4	116	0.694	99	86	77	63	38	0	..	..	..	3.63
“ “ N-5	0–No. 4	119	0.713	97	75	65	50	30	0	..	..	..	3.17
“ “ N-S	0–No. 8	107	0.640	100	100	67	33	0	..	..	..	..	3.00
“ “ N-3	0–No. 4	116	0.698	96	57	47	35	18	0	..	..	..	2.53
				SERIES 118.									
Brunswick sand	0–No. 14	96	0.577	99	79	11	0	..	..	..	..	..	1.89
Burnt shale slag	0–⅜ in.	77	0.610	79	70	58	43	22	1	0	..	..	2.73
Burnt shale slag	No. 8–¾ “	53	0.522	100	100	100	100	100	85	11	0	..	5.96
Celite	....	12	0.100	..	..	..	..	..	..	..	..	..	....
Mix of sand and shale slag[2]	0–¾ in.	73	0.618	92	86	74	67	59	38	5	0	..	4.70
Fine Elgin sand	0–No. 14	109	0.655	89	50	13	5	1	0	..	..	..	1.58
Elgin sand	0–No. 4	115	0.688	99	93	58	37	20	2	0	..	..	3.10
Elgin pebbles	No. 4–¾ in.	105	0.629	100	100	100	100	100	100	67	0	..	6.67
Elgin pebbles	No. 4–⅜ “	105	0.629	100	100	100	100	100	100	0	..	..	6.00
Slag	0–No. 4	100	0.666	94	89	80	63	40	0	..	..	..	3.66
Slag	No. 4–⅜ in.	90	0.599	100	100	100	100	100	100	0	..	..	6.00
Mix of sand and shale slag[2]	0–⅜ “	108	0.721	96	92	85	78	67	51	0	..	..	4.70
Elgin sand and pebbles	0–⅜ “	121	0.725	98	95	72	57	45	33	0	..	..	4.00
Elgin sand and pebbles	0–¾ “	127	0.762	99	97	80	71	63	54	36	0	..	5.00
				SERIES 120.									
Elgin sand	0–No. 28	105	0.629	90	50	0	..	..	..	..	..	..	1.40
“ sand	0–No. 14	107	0.641	96	87	31	0	..	..	..	..	..	2.14
“ sand	0–No. 8	109	0.653	99	89	45	17	0	..	..	..	..	2.50
“ sand	0–No. 4	115	0.688	99	91	59	36	20	0	..	..	..	3.05
“ sand and pebbles	0–⅜ in.	119	0.712	99	94	72	56	46	32	0	..	..	4.00
“ sand and pebbles	0–¾ “	126	0.754	99	96	81	71	63	54	36	0	..	5.00
“ sand and pebbles	0–1½“	128	0.767	99	98	87	81	75	68	50	17	0	5.75

[1] The sum of percentages in the Sieve Analysis, divided by 100.

[2] **Made up of 0.15 volumes of fine sand, 0.65 volumes of fine slag and 1.2 volumes of medium slag.**

aggregate were the same as those described above, except that blast-furnace slag was substituted for burnt shale. In the third group a 1:4 mix was used with sand and pebbles from Elgin, Ill. All tests were made at the age of 28 days.

Series 120 (begun December, 1918) was carried out with two cements, each ground at the mill to five finenesses varying from 2 to 43 per cent residue. The principal feature of the tests was a study of the effect of fineness for a wide range of mixtures, consistencies, size and grading of aggregates, and age of concrete. In two groups of tests measurements of elongation and contraction were made on 6 by 12-in. cylinders stored in damp sand, air and water. One-year tests in this series are not due.

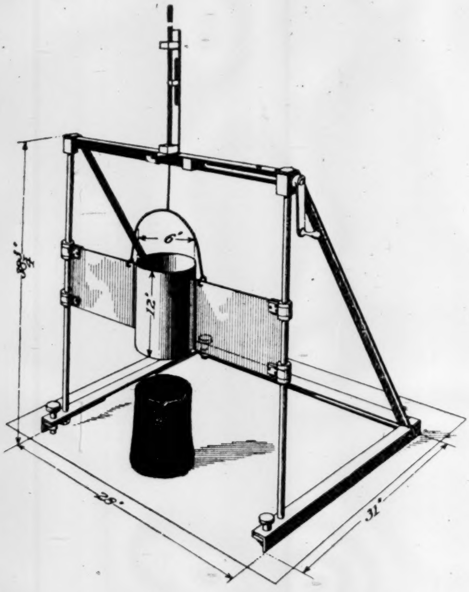

FIG. 1.—Apparatus used in "Slump" Tests of Workability of Concrete.

MATERIALS.

The cements used represented the product of seven commercial mills. The samples (except cements I) were ground from the same clinker to the different degrees of fineness shown in the tables. The finenesses used gave an extreme variation of 2 to 43 per cent residue on the No. 200 sieve. Each lot of cement is referred to by a letter, samples of different fineness being designated by an attached figure. The figure 1 following the letter designates the finest cement; the other finenesses follow in order. Miscellaneous tests of the cements are given in Tables IV and V. Table VI gives chemical analysis of the cements. Strength tests of the cements are included in the tables accompanying each series.

Sand and pebbles from a pit of the Chicago Gravel Co., near Elgin, Ill., were used as aggregate in most of the tests.

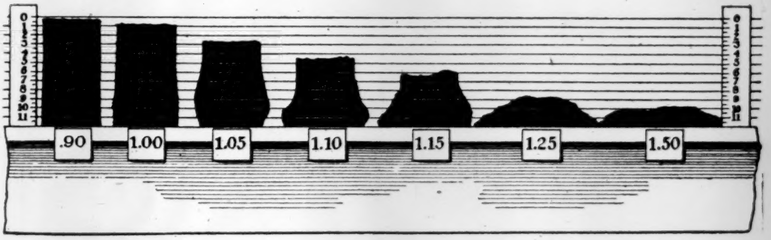

FIG. 2.—Sketch Showing Appearance of Concrete after "Slump" Tests.

The slump is measured on the vertical scale of inches. The sketch was made from a photograph of the concrete specimens after slump tests of 6 by 12-in. cylinders, using a 1:2½ mix, with sand and pebble aggregate graded to ¾ in. The figures under the specimens refer to the relative consistency of the concrete.

In Series 118 three different aggregates were used; burnt shale manufactured for the U. S. Shipping Board, mixed with small quantities of celite and fine sand from Brunswick, Ga.; aggregates consisting of Elgin sand and crushed blast-furnace slag up to $\frac{3}{8}$ in., and Elgin sand and pebbles. General information concerning aggregates will be found in Table VII. In cases where different sizes of Elgin sand were used, the material was obtained by screening out the coarser sizes from the commercial product. The pebbles were screened to three sizes (No. 4 to $\frac{3}{8}$ in.; $\frac{3}{8}$ to $\frac{3}{4}$ in. and $\frac{3}{4}$ to $1\frac{1}{2}$ in.) and recombined for each batch to the sieve analysis shown.

The "fineness modulus" of an aggregate is used as a measure of its size and grading. It is the sum of the percentages in the sieve analysis divided by 100. The sieve analysis is expressed in terms of weight or separate volumes coarser than each sieve. The sizes of sieves and fineness modulus of the aggregates used in these tests are shown in Table VII. Low values of fineness modulus (abbreviated to F. M. in the tables) correspond to small sizes and high values to the coarse sizes of aggregate.[1]

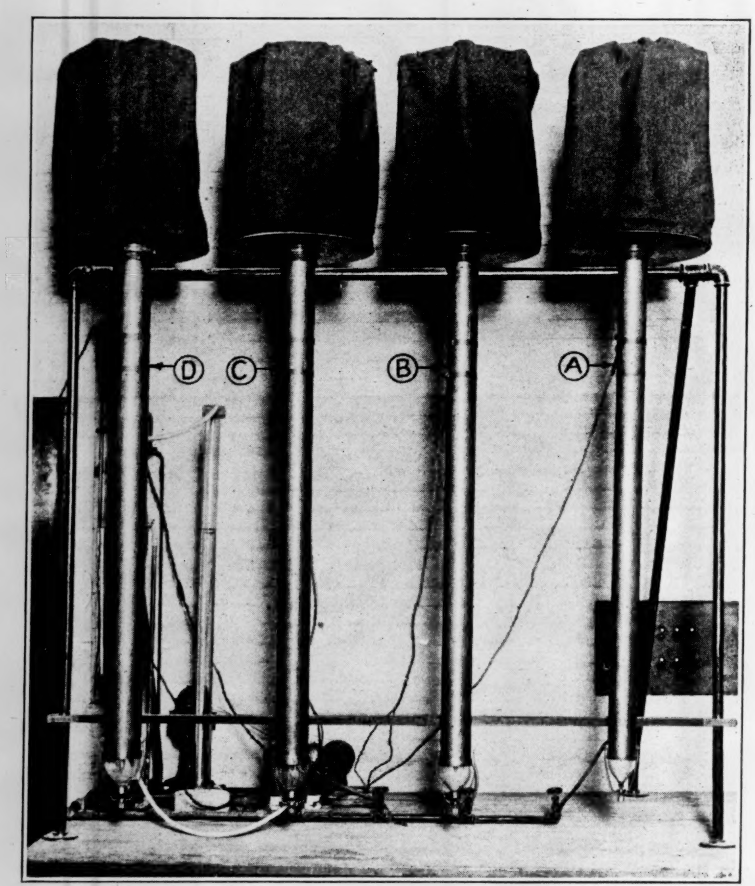

FIG. 3.—Air Analyzer for Mechanical Analysis of Cement.
For details of tests see Table V.

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[1] For further details on fineness modulus of aggregates see the writer's report on "Design of Concrete Mixtures," *Bulletin No. 1*, Structural Materials Research Laboratory, Lewis Institute.

TEST PIECES.

The kind and numbers of test pieces used in each series are indicated in the outlines of the series, Tables I to III. Specimens for compression tests of concrete consisted of 6 by 12-in. cylinders. Over 6100 specimens of this kind were tested. The concrete for each cylinder was proportioned separately and mixed by hand with a bricklayer's trowel in a shallow metal pan. Each batch consisted of about $\frac{1}{5}$ cu. ft. of concrete. The forms consisted of 12-in. lengths of cold-drawn steel tubing split along one element. Each form stood on a machined cast-iron base plate. The specimens were molded by hand by placing the fresh concrete in the form in 4-in. layers and puddling with about 25 strokes of a $\frac{5}{8}$-in. round steel bar pointed at the lower end. A smooth top was formed by means of a neat cement cap placed on the cylinder from 2 to 4 hours after molding. The cement paste for capping was mixed at the same time, or prior to the mixing of the concrete. About 24 hours after molding the specimen, the metal form was removed and the specimen weighed, marked and stored in damp sand until the date of test.

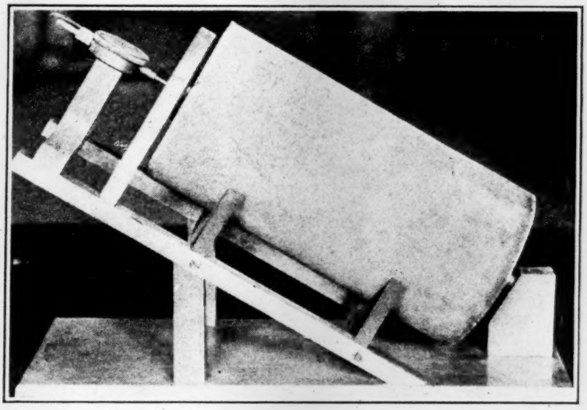

FIG. 4.—Apparatus for Measuring Elongation and Contraction of 6 by 12-in. Cylinders.

The mixtures in Series 20 and 31 are expressed in terms of the volume of cement, fine aggregate and coarse aggregate—for

TABLE VIII.—TENSION TESTS OF BRIQUETTES—SERIES 20.

Specimens stored in water; tested wet.
Each value is the average of 4 tests made on different days.

Cement.		Tensile Strength, lb. per sq. in.																				
Ref. No.	Fineness, Residue on No. 200 Sieve.	Neat.						1:2 Standard Sand.					1:3 Standard Sand.					1:4 Standard Sand.				
		1 d.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	317	588	694	713	651	660	392	516	490	498	538	291	383	451	441	453	202	320	350	340	310
A-2	16.9	291	651	665	704	661	705	376	529	624	571	523	240	354	419	441	404	243	338	366	370	346
A-3	19.9	296	576	771	706	718	625	380	506	574	492	535	242	401	375	406	394	158	271	309	342	300
A-4	22.9	275	614	655	783	721	718	339	519	553	522	538	252	360	423	431	384	160	266	329	322	283
B-1	12.1	238	550	719	719	678	635	415	478	511	499	503	289	373	361	378	350	223	341	294	312	296
B-2	16.5	273	644	684	723	692	655	409	520	499	515	498	300	370	341	382	351	215	296	289	304	284
B-3	20.4	293	604	765	658	692	648	384	472	483	492	478	244	379	341	361	323	189	288	281	314	265
B-4	23.0	285	636	669	685	704	668	379	455	456	500	494	270	358	350	369	325	208	266	273	318	263
C-1	16.1	356	699	896	828	776	735	451	621	633	649	518	305	441	479	463	418	260	376	406	394	339
C-2	20.6	408	711	754	778	859	738	460	621	628	570	555	342	465	501	435	403	261	354	409	380	353
C-3	26.5	438	733	830	799	869	945	434	601	634	596	560	288	423	470	425	396	231	306	388	345	301
C-4	33.3	353	719	870	936	919	840	391	519	615	588	533	238	391	439	426	396	190	311	366	354	293
D-1	16.1	340	721	685	733	668	648	400	520	576	598	569	259	385	434	448	405	222	360	348	380	316
D-2	20.3	372	638	766	739	718	653	431	559	623	576	538	314	420	474	444	406	218	338	371	378	361
D-3	22.3	404	649	730	708	670	740	388	554	608	578	511	280	413	446	478	385	215	301	384	369	300
D-4	25.6	371	600	759	734	759	723	371	506	580	544	476	268	373	430	404	334	204	290	349	350	299
E-1	10.6	341	639	683	640	568	550	465	510	587	556	620	358	388	440	438	475	305	300	414	423	325
E-2	15.3	349	620	714	654	618	645	480	571	592	570	564	355	405	452	474	479	255	271	370	380	341
E-3	18.9	370	731	748	675	618	680	464	515	579	544	518	356	351	433	466	423	284	311	364	351	308
E-4	23.7	349	626	733	740	667	663	373	510	560	569	529	313	366	421	454	385	231	304	350	369	349
Average		336	647	740	783	711	694	409	530	570	551	530	290	390	424	428	394	224	310	351	355	312

TABLE VIII—*Continued.*

Cement.		Tensile Strength, lb. per sq. in.																				
		Neat.						1:2 Elgin Sand.					1:3 Elgin Sand					1:4 Elgin Sand.				
Ref. No.	Fineness Residue on No. 200 Sieve.	1 d.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	....	....	....	....	....	....	478	539	698	669	706	396	529	600	575	640	336	471	513	501	564
A-2	16.9	....	....	....	....	....	....	421	600	644	605	741	334	518	582	579	614	306	414	506	509	514
A-3	19.9	....	....	....	....	....	....	429	546	636	638	701	335	490	501	596	596	245	391	456	508	531
A-4	22.9	....	....	....	....	....	....	423	602	591	612	681	324	478	588	566	585	262	385	480	442	485
B-1	12.1	....	....	....	....	....	....	450	551	565	529	659	391	484	515	568	593	318	429	441	465	516
B-2	16.5	....	....	....	....	....	....	449	504	601	638	649	410	514	524	560	611	301	400	493	464	504
B-3	20.4	....	....	....	....	....	....	404	454	549	584	585	373	426	526	532	571	260	379	455	465	491
B-4	23.0	....	....	....	....	....	....	410	540	509	578	656	323	459	533	482	574	296	359	444	424	509
C-1	16.1	....	....	....	....	....	....	500	676	820	695	788	474	534	660	656	730	350	464	558	571	634
C-2	20.6	....	....	....	....	....	....	521	660	734	736	800	454	558	648	626	720	328	459	549	535	570
C-3	26.5	....	....	....	....	....	....	494	686	700	719	659	421	498	608	593	623	293	409	493	491	536
C-4	33.3	....	....	....	....	....	....	435	636	660	658	681	309	440	544	576	639	218	339	484	474	539
D-1	16.1	....	....	....	....	....	....	468	591	660	634	656	406	533	564	636	568	303	405	454	489	534
D-2	20.3	....	....	....	....	....	....	502	576	729	625	694	390	503	619	616	650	333	391	484	519	560
D-3	22.3	....	....	....	....	....	....	474	581	654	650	676	374	466	591	580	664	304	426	510	480	541
D-4	25.6	....	....	....	....	....	....	440	523	656	618	664	351	474	589	545	538	282	370	460	489	490
E-1	10.6	....	....	....	....	....	....	559	549	711	673	788	493	513	639	654	665	374	438	544	545	540
E-2	15.3	....	....	....	....	....	....	560	519	674	743	686	441	485	577	615	679	359	391	529	571	550
E-3	18.9	....	....	....	....	....	....	520	598	675	658	701	443	513	600	548	651	353	419	494	504	549
E-4	23.7	....	....	....	....	....	....	555	578	621	681	730	378	506	539	606	625	291	345	494	494	568
Average	....	....	....	....	....	....	....	475	575	654	647	695	391	496	577	585	627	306	404	492	497	536

TABLE IX.—COMPRESSION TESTS OF 2 BY 4-IN. CYLINDERS—SERIES 20.

Specimens stored in water; tested wet.
Each value is the average of 4 tests made on different days.

Cement.		Compressive Strength, lb. per sq. in.														
		1:2 Standard Sand.					1:3 Standard Sand.					1:4 Standard Sand.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	2940	5070	6620	6790	6960	1600	3200	4060	4140	4180	1030	1680	2330	2400	2710
A-2	16.9	2370	4690	6050	5640	6570	1310	2950	3460	3820	4230	860	1550	2010	2200	2250
A-3	19.9	2290	4720	6180	5740	6870	1240	2650	3310	3380	4040	890	1410	2030	1950	1970
A-4	22.9	2250	4500	6080	6270	7290	1230	2610	3160	3640	3690	710	1290	1570	1910	2180
B-1	12.1	2880	4980	5780	6080	6760	1820	3030	3800	3600	4280	1000	1950	2310	2040	2250
B-2	16.5	3220	5360	6560	6600	6350	1870	3240	3720	4110	3950	1108	1860	2300	2140	2190
B-3	20.4	2390	4500	5750	5810	5860	1440	2740	3370	3400	3560	870	1720	1790	1820	2110
B-4	23.0	2650	4610	5670	5800	6330	1440	2540	3270	2990	3530	940	1520	2130	1640	1950
C-1	16.1	3980	7060	8530	9440	9600	2060	3700	5130	5360	5640	1100	1870	2620	2790	2910
C-2	20.6	3490	6240	8510	8640	9030	1700	3330	4360	5030	5220	1080	1750	2340	2560	2780
C-3	26.5	3230	5480	7250	8020	8030	1590	2610	3690	3970	4160	810	1810	2100	2360	2420
C-4	33.3	2660	4850	6760	6960	7310	1420	2230	3500	3710	3500	670	1210	1990	2210	1750
D-1	16.1	3130	5040	6170	6730	7410	1600	2760	3620	4380	4270	810	1820	2020	2640	2650
D-2	20.3	3140	5640	6910	7260	7280	1650	2920	3940	4220	4520	1180	1660	2450	2500	2850
D-3	22.3	2870	4950	6280	7150	7380	1670	2910	3920	3840	4300	960	1940	2380	2600	2630
D-4	25.6	2850	5160	6690	5990	7370	1550	2830	3940	3700	4150	640	1700	1800	2200	2190
E-1	10.6	4110	5970	6990	8160	7920	2450	4200	4630	5370	5370	1490	2430	2920	2990	2810
E-2	15.3	3940	6020	7030	7110	8110	2350	3510	4460	4980	5060	1350	1790	2660	2970	3240
E-3	18.9	4080	6430	7270	7850	8190	2440	3470	4660	4200	4550	1460	2170	3050	2840	2640
E-4	23.7	3230	5540	6950	6800	7350	1930	2620	3900	4180	4760	1390	2170	2690	3060	3230
Average		3090	5340	6700	6940	7400	1720	3000	3900	4100	4350	1020	1770	2270	2390	2940

TABLE IX—*Continued.*

Cement.		Compressive Strength, lb. per sq. in.														
		1:2 Elgin Sand.					1:3 Elgin Sand.					1:4 Elgin Sand.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1.....	12.5	3770	5860	6980	8000	7800	2840	4910	6260	6430	6980	2090	3620	5000	5040	5280
A-2.....	16.9	3070	5610	7090	7250	7210	2500	4540	5810	6080	6850	1760	3460	4230	4560	4790
A-3.....	19.9	3000	5430	6950	6490	7590	2260	4470	5600	5790	6590	1500	2930	4100	4100	4450
A-4.....	22.9	2890	4990	7080	6840	7640	2270	4050	5160	5800	6360	1320	2510	3620	3910	4350
B-1.....	12.1	3480	5580	6680	7060	7580	3000	4770	5590	5590	6900	2260	3540	4660	4590	5090
B-2.....	16.5	3680	5930	7320	7610	7830	2960	4780	5720	6060	6480	2170	3450	3960	4490	4900
B-3.....	20.4	3250	5260	6350	7000	7400	2600	4410	5800	5700	6220	1760	2990	3660	4090	4500
B-4.....	23.0	3240	5430	5920	6690	7210	2400	4050	5570	5490	5840	1880	3060	3900	4010	4140
C-1.....	16.1	4320	7170	8540	9810	9840	3150	5240	7380	8180	8380	2150	3690	4760	5460	5940
C-2.....	20.6	4550	6940	8860	9250	9580	3140	5620	6850	7740	7850	1750	3380	4340	5010	5270
C-3.....	26.5	4000	6300	8320	9610	9700	2820	4540	6320	6850	7580	1880	3040	4260	4820	5380
C-4.....	33.3	3460	5680	7770	7940	7910	2300	3810	5600	5770	6560	1480	2470	3420	3850	4360
D-1.....	16.1	3990	5930	6870	7660	8660	2870	4620	5830	6480	7520	2240	3530	4070	4740	5430
D-2.....	20.3	3780	6160	8050	8530	9310	2810	4730	6040	6440	7280	2140	3780	4800	5230	5710
D-3.....	22.3	3850	6030	7460	8390	9020	2850	4780	6330	6790	7430	2010	3380	4740	4890	5790
D-4.....	25.6	3650	6160	7170	8130	9230	2560	4800	5880	6350	6700	1830	3400	4280	4680	5110
E-1.....	10.6	4930	7000	8300	9480	9630	4320	5920	7380	8360	8800	2930	4520	5790	5810	6660
E-2.....	15.3	4460	6780	7540	8430	10130	3890	5650	6930	7080	8270	2750	3650	4530	5220	6210
E-3.....	18.9	4690	6580	7250	8080	9480	3760	5720	6550	7210	8030	2760	4000	4330	5410	6810
E-4.....	23.7	4770	6580	7590	8400	9120	3330	4970	6280	6180	7860	2550	3480	4310	5440	5510
Average	....	3840	5070	7400	8030	8590	2930	4820	6140	6520	7220	2070	3390	4340	4770	5280

instance 1:2:4—indicating a mixture in the proportions of 1 sack of cement (1 cu. ft. = 94 lb.), 2 cu. ft. of sand and 4 cu. ft. of coarse aggregate. The actual quantities for a batch were determined by weight, on the basis of the unit weights of the materials. In Series 118 and 120 the mixtures are expressed as one volume of cement to a given number of volumes of aggregate, regardless of the size and grading of the latter. A 1:5 mix expressed in this manner is about the same as the usual 1:2:4. The exact equivalent of the latter will vary with the size and grading of the aggregate. This is the best method of expressing concrete mixtures. For ordinary mixtures the quantity of finished concrete is nearly equal to the volume of *mixed* aggregate. Wide variations are found if we attempt to compute yield of concrete in any other way due to differences in

TABLE X.—COMPRESSION TESTS OF 6 BY 12-IN. CYLINDERS—SERIES 20.

Sand and pebble aggregate from Elgin, Ill., graded 0–1¼ in.
Specimens stored in damp sand; tested damp.
Each value is the average of 4 tests made on different days.

ALL VALUES IN POUNDS PER SQUARE INCH.

Cement.		1:2:4 Concrete.					1:3:5 Concrete.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A 1	12.5	1690	3050	4100	4310	5110	1100	1820	2800	3140	3620
A 2	16.9	1560	2530	3720	4080	4450	920	1570	2420	2870	3090
A 3	19.9	1310	2310	3710	3880	4410	740	1390	2300	2460	3260
A 4	22.9	1260	2370	3410	4180	4340	810	1480	2130	2790	2810
B 1	12.1	1890	3120	3980	4440	4920	1390	2130	2920	3340	3520
B 2	16.5	1880	3000	3960	4440	4570	1130	1970	2810	3020	3320
B 3	20.4	1670	2500	3630	3650	4540	930	1660	2210	2630	3080
B 4	23.0	1530	2470	3280	3720	3940	950	1630	2190	2360	2800
C 1	16.1	1990	3530	4780	5220	6020	1330	2400	3170	3810	4100
C 2	20.6	1970	3490	4700	5510	5800	1200	2350	3410	3470	3720
C 3	26.5	1750	3020	4300	4910	5360	1040	1770	2640	2880	3410
C 4	33.3	1300	2220	3460	4080	4760	840	1580	2180	2650	2930
D 1	16.1	1700	3220	4110	4410	5110	980	2130	2960	3350	3760
D 2	20.3	1790	3290	4090	4590	5330	1120	2310	3160	3490	3950
D 3	22.3	1600	3050	4100	4480	5220	1020	2080	2980	3440	3510
D 4	25.6	1440	2820	4050	4220	4890	990	2040	2520	3210	3610
E 1	10.6	2250	3420	5090	5180	5830	1660	2740	4030	4280	4930
E 2	15.3	2220	3220	4650	5070	5940	1400	2270	3450	3890	4310
E 3	18.9	2060	3410	4520	5070	5340	1550	2420	3180	3720	4170
E 4....	23.7	1880	3030	4120	4630	5480	1300	2210	3280	3630	3770
Average....................		1740	2950	4090	4500	5070	1120	2000	2840	3220	3580

total volume produced by mixing fine and coarse aggregate of widely different size and grading.

The 2 by 4-in. mortar cylinders used in several of the series were made in steel molds similar to those described above. Sufficient mortar was mixed to make four or five specimens; one from each batch was tested at each of the ages shown. The mortar was placed in the molds in three or four layers. These cylinders were stored in water and tested in a damp condition.

TABLE XI.—QUANTITY OF MIXING WATER—SERIES 20.

Strength tests given in Tables VIII, IX and X.

Cement.			Water—per cent by weight of Dry Material.				Ratio of Water to Volume of Cement.					
Ref. No.	Fineness. Residue on Sieve No.		Neat.[1]	Sand Mortar.[2]			Neat.[1]	Sand Mortar.[2]			Concrete.	
	100	200		1:2	1:3	1:4		1:2	1:3	1:4	1:2:4	1:3:5
A-1	1.7	12.5	23.0	11.8	10.3	9.5	0.35	0.54	0.62	0.72	0.76	0.91
A-2	2.8	16.9	23.0	11.8	10.3	9.5	0.36	0.55	0.64	0.74	0.79	0.94
A-3	3.6	19.9	22.5	11.8	10.3	9.5	0.36	0.56	0.65	0.75	0.80	0.97
A-4	4.3	22.9	22.0	11.6	10.2	9.3	0.36	0.56	0.66	0.74	0.82	1.01
B-1	1.5	12.1	23.0	11.8	10.3	9.5	0.35	0.53	0.62	0.71	0.76	0.91
B-2	2.2	16.5	23.0	11.8	10.3	9.5	0.36	0.55	0.64	0.74	0.78	0.95
B-3	3.5	20.4	23.0	11.8	10.3	9.5	0.36	0.56	0.65	0.75	0.80	0.97
B-4	4.5	23.0	23.0	11.8	10.3	9.5	0.37	0.57	0.67	0.76	0.82	1.00
C-1	2.8	16.1	21.0	11.3	10.0	9.2	0.33	0.53	0.62	0.71	0.75	0.95
C-2	4.7	20.6	20.0	11.1	9.8	9.1	0.32	0.53	0.62	0.72	0.77	0.95
C-3	9.3	26.5	19.5	11.1	9.8	9.1	0.31	0.54	0.63	0.74	0.78	0.97
C-4	13.3	33.3	19.0	10.9	9.7	8.9	0.31	0.54	0.64	0.74	0.79	0.99
D-1	1.8	16.1	22.5	11.7	10.3	9.5	0.35	0.54	0.64	0.74	0.77	0.98
D-2	2.4	20.3	22.0	11.6	10.2	9.5	0.35	0.55	0.64	0.75	0.79	1.00
D-3	4.1	22.3	21.5	11.4	10.1	9.3	0.34	0.55	0.65	0.74	0.80	1.01
D-4	5.0	25.6	21.0	11.3	10.0	9.2	0.34	0.55	0.64	0.74	0.80	1.02
E-1	1.2	10.6	24.5	12.1	10.6	9.7	0.36	0.54	0.63	0.72	0.77	0.96
E-2	1.8	15.3	24.0	12.0	10.5	9.6	0.37	0.56	0.65	0.74	0.80	0.99
E-3	2.9	18.9	23.5	11.9	10.4	9.6	0.37	0.56	0.65	0.76	0.82	1.01
E-4	4.9	23.7	23.0	11.8	10.3	9.5	0.37	0.57	0.66	0.76	0.85	1.05

[1] Normal consistency of cement.

[2] Same amount of water used for Standard Ottawa and Elgin sand mortars.

Briquette tests were made on all cements. The results of the tests on neat cement and sand mortars at ages of 7 days to 1 year are given in Tables VIII, XII and XVII. The batches for the briquette tests were mixed by hand in the manner described in the standard cement specifications. The batches were of such size that four or five briquettes could be made; one from each batch was tested at the ages shown. The mortar used in the four or five specimens in a set was mixed on different days. Briquettes were stored in water and tested wet.

The water content of the concrete is expressed in terms of the "relative consistency" or the "water-ratio." Relative consistency of 1.00 (normal consistency) is of such plasticity that the concrete of usual mixes will slump $\frac{1}{2}$ to 1 in. if the metal form is withdrawn by a steady, upward pull immediately after molding the cylinder by the method described above.

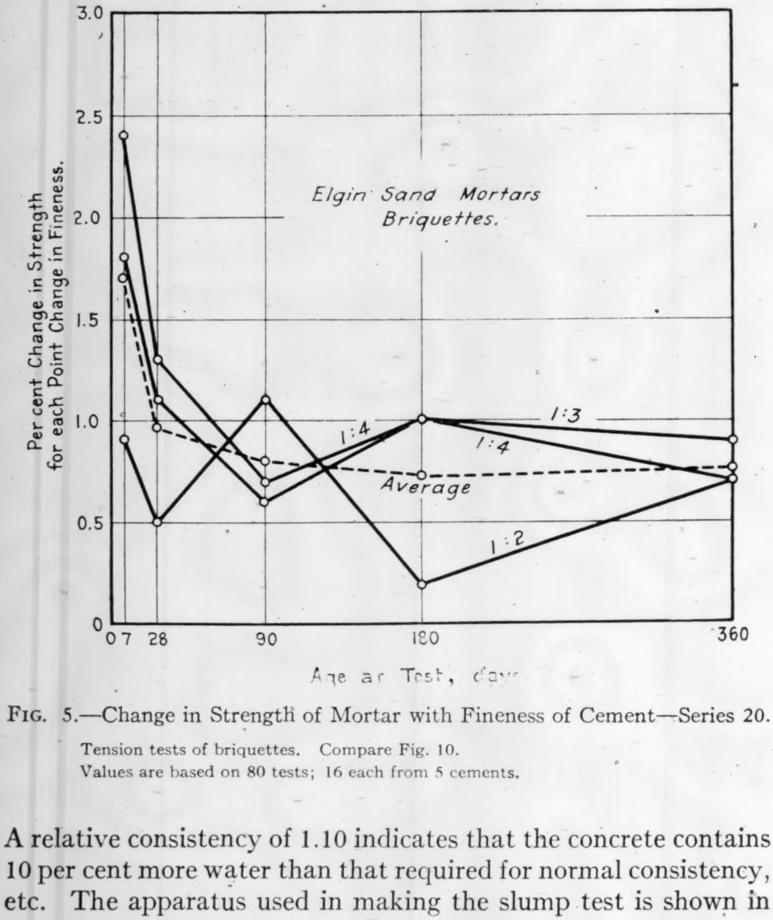

FIG. 5.—Change in Strength of Mortar with Fineness of Cement—Series 20.

Tension tests of briquettes. Compare Fig. 10.
Values are based on 80 tests; 16 each from 5 cements.

A relative consistency of 1.10 indicates that the concrete contains 10 per cent more water than that required for normal consistency, etc. The apparatus used in making the slump test is shown in Fig. 1. It consists of a framework carrying a 6 by 12-in. metal form on vertical guides and a windlass for lifting the form.

The frame stands on leveling screws. The slump is measured from the original height of 12 in. to the top of the concrete after the removal of the form. A measuring rod enables the operator to determine the slump directly.

Fig. 2 is a sketch showing the form taken by the concrete cylinders of different consistencies after the slump test. Slump

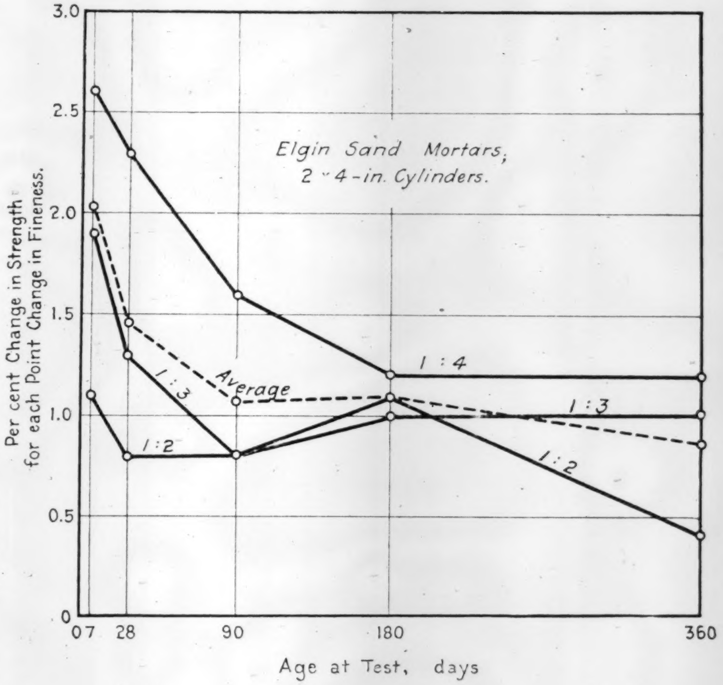

FIG. 6.—Change in Strength of Mortar with Fineness of Cement—Series 20.

Compression tests of 2 by 4-in. cylinders. Compare Fig. 10.
Values are based on 80 tests; 16 each from 5 cements.

tests were carried out on all specimens in Series 118 and 120. After the slump test was made the same concrete was remolded for the compression test.

The "water-ratio" is the ratio of volume of water to volume of cement in the batch. The weight of all cements was assumed as 94 lb. per cu. ft. A rich mixture will give a low water-ratio and a lean mixture a high water-ratio. The distinction between the relative consistency and water-ratio should be made clear. The relative consistency refers to the *plastic condition* of the concrete without reference to the actual quantity of water as compared to the cement; while the water-ratio refers to the *actual quantity of water* as compared with the cement, and takes no account of the plasticity of the concrete.

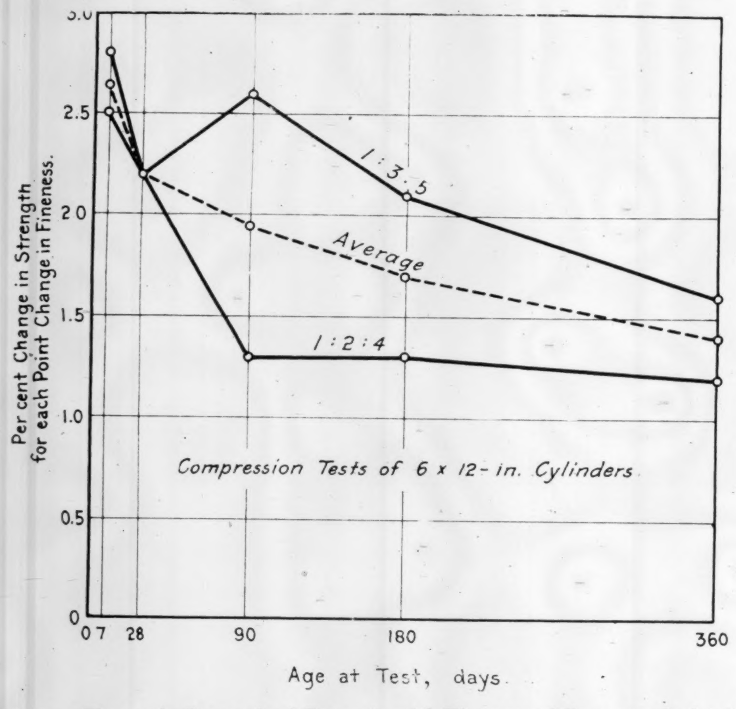

FIG. 7.—Change in Strength of Concrete with Fineness of Cement—Series 20.

Compression tests of 6 by 12-in. cylinders. Compare Fig. 11.
Values are based on 80 tests; 16 each from 5 cements.

In general, the five concrete test cylinders in a set were made on five different days. One specimen of each group was made before starting the second round. The strengths given in the tables are, therefore, the average of five entirely independent tests. In this way minor variations in materials, proportions, manipulation, etc., are eliminated.

TABLE XII.—TENSION TESTS OF BRIQUETTES—SERIES 31.

Specimens stored in water; tested wet.
Each value is the average of 5 tests made on different days.

ALL VALUES IN POUNDS PER SQUARE INCH.

Cement.		Neat Cement.					1:3 Standard Sand Mortar.					1:3 Elgin Sand Mortar.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1	4.9	532	500	490	476	456	335	435	486	425	375	436	499	570	607	564
F-2	8.7	569	522	545	520	400	310	418	454	425	360	403	540	595	656	512
F-3	14.2	566	565	590	596	472	295	383	433	392	355	401	448	531	565	521
F-4	17.9	596	632	636	556	443	294	362	409	391	346	327	431	533	546	528
F-5	24.5	609	677	650	640	570	262	312	376	369	312	311	402	489	527	458
F-6	28.1	587	685	684	590	562	228	335	342	309	312	291	390	406	487	461
F-7	33.4	587	664	682	698	594	239	302	329	299	268	292	341	377	457	388
G-1	2.2	500	548	504	466	435	311	416	457	424	364	380	497	570	609	527
G-2	7.9	522	610	590	554	506	276	423	442	443	367	331	478	522	586	478
G-3	12.9	589	662	676	660	521	289	395	449	404	406	369	468	585	591	569
G-4	19.9	568	644	621	632	502	282	343	451	350	359	334	447	530	553	517
G-5	25.2	559	624	684	672	509	257	347	376	359	307	279	373	461	536	492
G-6	29.6	603	638	756	622	571	248	337	383	358	322	306	416	471	545	498
G-7	34.0	534	650	728	718	627	235	287	352	315	288	282	366	400	475	466
H-1	12.0	606	594	618	586	489	316	435	432	421	382	393	491	596	542	549
H-2	19.9	487	716	734	669	550	254	404	470	440	395	285	444	566	602	532
H-3	23.3	632	670	732	648	601	301	445	452	368	341	325	476	543	552	529
H-4	25.1	704	702	668	748	648	292	413	419	361	336	332	454	531	556	514
H-5	30.1	702	746	794	676	615	266	384	384	312	331	302	426	483	485	440
Average		582	634	652	617	530	278	378	416	377	344	336	441	514	551	502

TABLE XIII.—COMPRESSION TESTS OF 2 BY 4-IN. CYLINDERS—SERIES 31.

Specimens stored in water; tested wet.
Each value is the average of 5 tests made on different days.

ALL VALUES IN POUNDS PER SQUARE INCH.

Cement.		1:3 Standard Sand Mortar.										1:3 Elgin Sand Mortar.				
		Made March, 1916.					Made August, 1916.					Made March, 1916.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1	4.9	3020	4770	5680	6330	5700	2590	4040	4970	5160	5860	3520	5620	6540	7000	7170
F-2	8.7	2860	4050	5040	5720	5570	2380	3890	4760	5060	5720	3620	5720	6530	7040	7130
F-3	14.2	2190	3580	4570	4680	4970	1990	3110	4020	4540	5150	2890	5050	6220	6720	6900
F-4	17.9	2090	3230	4020	4370	4890	2090	3240	4080	4560	5080	2910	4640	5880	6740	5720
F-5	24.5	1810	2890	3460	4110	4190	1880	3010	3890	4050	4520	2660	4380	5340	6030	6340
F-6	28.1	1740	2750	3610	3890	3310	1520	2520	3350	3560	3680	2260	4070	4890	5700	5720
F-7	33.4	1410	2160	3100	3220	3090	1480	2370	3100	3480	3360	2100	3410	4530	4850	5160
G-1	2.2	2490	3620	5250	5150	5300	2490	4070	5760	5750	6650	3090	4630	6220	6530	6060
G-2	7.9	1740	3190	4430	4300	4310	1940	3830	5100	4970	5580	2600	4480	5500	6250	6400
G-3	12.9	2010	3180	4780	4710	4620	1910	3600	4830	5020	5590	3240	5350	6770	7220	7560
G-4	19.9	1620	3070	4310	4070	4590	1780	3100	4010	4570	4760	2760	4510	5500	6210	6840
G-5	25.2	1660	2980	4010	4140	3870	1340	2400	3290	3770	4250	2500	4240	5660	5970	6310
G-6	29.6	1650	2640	4070	3710	3560	1500	2560	3510	3660	4360	2230	4090	5250	5660	6090
G-7	34.0	1350	2440	3410	3260	3180	1050	1990	2820	2960	3680	2150	3740	4400	5300	5490
H-1	12.0	2240	4070	4830	5020	5220	2290	3960	4770	4570	5590	3010	5710	6530	7040	6740
H-2	19.9	1800	3490	4260	4520	4560	2010	3320	4570	4500	5440	2410	4590	5530	6290	7030
H-3	23.3	1950	3400	3930	4210	4060	1900	3240	3800	4320	4970	2670	4610	5970	6140	6730
H-4	25.1	1980	3300	3800	3870	4000	1900	3060	3880	4230	4550	2570	4880	5850	6200	6570
H-5	30.1	1600	2680	3480	3440	3410	1620	2590	3640	3510	4050	1980	3730	4560	5120	5240
Average		1960	3240	4210	4350	4340	1880	3150	4110	4330	4890	2690	4600	5670	6210	6380

TABLE XIV.—COMPRESSION TESTS OF 6 BY 12-IN. CYLINDERS—SERIES 31.

Sand and pebble aggregate from Elgin, Ill., graded 0–1¼ in.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests made on different days.

Cement.		Compressive Strength, lb. per sq. in.														
Ref. No.	Fineness, Residue on No. 200 Sieve.	1:1½:3 Concrete.					1:1¾:3½ Concrete.					1:2:4 Concrete.				
		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1.....	4.9	3200	4480	5680	6200	6300	2970	4420	5180	5600	6020	2600	3820	4780	5420	5540
F-2.....	8.7	2910	4370	5430	5790	6010	2730	3920	4880	5520	5560	2350	3680	4580	5240	5280
F-3.....	14.2	2570	3980	4980	5630	5800	2290	3620	4570	5090	5310	2010	3310	4130	4560	4680
F-4.....	17.9	2440	3720	4900	5540	5970	2150	3390	4470	4850	5330	1890	3010	4010	4610	4680
F-5.....	24.5	2140	3520	4420	5080	5470	1900	2970	4030	4520	4900	1540	2570	3430	4020	4260
F-6.....	28.1	1960	3170	4230	4850	5310	1620	2680	3550	4370	4320	1410	2290	3180	3470	4100
F-7.....	33.4	1670	2910	3860	4320	4770	1490	2490	3410	3790	4170	1230	2030	2960	3110	3670
G-1.....	2.2	2880	4210	5320	5600	6100	2490	3850	4880	5470	5750	2420	3810	4830	5150	5240
G-2.....	7.9	2290	3840	5030	5720	5910	2080	3530	4660	4990	5620	1970	3400	4410	4760	5020
G-3.....	12.9	2430	3990	5270	5560	5590	2080	3460	4670	5100	5330	1950	3200	4460	4850	4990
G-4.....	19.9	2020	3520	4660	5220	5340	1790	3180	4290	4510	4770	1650	2940	3980	4150	4820
G-5.....	25.2	1650	3130	4460	4930	5250	1450	2600	3700	4370	4690	1290	2490	3550	3930	4310
G-6.....	29.6	1790	3130	4300	4940	5340	1610	2850	3880	4440	4660	1450	2490	3660	4030	4420
G-7.....	34.0	1480	2670	3920	4430	4800	1230	2430	3470	4020	4170	1080	2000	3010	3540	3780
H-1.....	12.0	2180	4010	5430	6060	6460	2120	4070	5070	5770	6270	1740	3530	4690	5070	5500
H-2.....	19.9	1300	3360	4710	5160	5700	1090	3050	4390	5060	5490	1160	2590	3760	4350	4590
H-3.....	23.3	2090	3780	4670	5210	5680	1740	3220	4230	5100	5310	1510	2900	3870	4320	4700
H-4.....	25.1	1990	3370	4330	5160	5560	1620	3100	4160	4670	5110	1500	2900	3680	4150	4640
H-5.....	30 1	1720	3090	3810	4290	4750	1540	2690	3640	4200	4710	1210	2190	3110	3560	3760
Average...............		2140	3590	4710	5250	5600	1890	3240	4280	4810	5230	1680	2910	3900	4340	4630

TABLE XIV—*Continued.*

Cement.		Compressive Strength, lb. per sq. in.														
Ref. No.	Fineness, Residue on No. 200 Sieve.	1:2½:5 Concrete.					1:3:6 Concrete.									
		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1.....	4.9	2070	3270	4240	4550	4830	1370	2420	3160	3480	3690	....	....	....	....	....
F-2.....	8.7	1980	2970	3900	4260	4680	1270	2090	2910	3240	3440	....	....	....	....	....
F-3.....	14.2	1590	2580	3280	3860	4000	990	1760	2500	2820	3020	....	....	....	....	....
F-4.....	17.9	1450	2390	3210	3630	3780	970	1780	2450	2800	2910	....	....	....	....	....
F-5.....	24.5	1250	2060	2890	3240	3500	880	1480	2100	2410	2550	....	....	....	....	....
F-6.....	28.1	1110	1880	2610	2980	3320	780	1360	2010	2300	2420	....	....	....	....	....
F-7.....	33.4	990	1710	2390	2780	2950	640	1200	1790	1990	2160	....	....	....	....	....
G-1.....	2.2	1790	3060	4010	4420	4580	1130	19[illegible]0	2970	3290	3550	....	....	....	....	....
G-2.....	7.9	1440	2590	3550	3890	4330	870	1610	2580	3060	3200	....	....	....	....	....
G-3.....	12.9	1370	2520	3450	3840	4160	870	1630	2530	2900	3150	....	....	....	....	....
G-4.....	19.9	1260	2320	3150	3480	3800	730	1480	2260	2510	2800	....	....	....	....	....
G-5.....	25.2	950	1810	2750	3100	3300	600	1130	1870	2170	2330	....	....	....	....	....
G-6.....	29.6	950	1750	2630	3100	3170	680	1250	1910	2280	2450	....	....	....	....	....
G-7.....	34.0	730	1450	2170	2550	2770	510	980	1600	1910	2090	....	....	....	....	....
H-1.....	12.0	1230	2710	3860	4200	4410	870	2010	2770	3130	3410	....	....	....	....	....
H-2.....	19.9	860	1960	2930	3380	3680	590	1390	2200	2560	2790	....	....	....	....	....
H-3.....	23.3	1030	2090	2990	3430	3700	750	1540	2370	2570	2790	....	....	....	....	....
H-4.....	25.1	1030	1950	2820	3220	3500	750	1430	2140	2470	2780	....	....	....	....	....
H-5.....	30.1	850	1620	2310	2720	3100	610	1150	1780	2150	2270	....	....	....	....	....
Average..................		1260	2200	3120	3510	3780	840	1560	2310	2640	2830					

METHODS OF TESTING.

The specimens for strength tests remained in damp sand or water until due to be tested; tests were made with specimens in wet or damp condition.

All tests of cement were carried out in accordance with the methods described in the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials. Extreme care was taken in the determination of fineness, normal consistency, etc. In Series 31, 118 and 120 samples of cement were tested for fineness each day that a given cement was used. In this way an average of 15 to 18 tests was secured. Fineness tests were made with a mechanical sieve shaker. The sieves were calibrated by comparison with cement samples of standard fineness supplied by the Bureau of Standards.

TABLE XV.—QUANTITY OF MIXING WATER—SERIES 31.

Strength tests given in Tables XII, XIII and XIV.

Cement.		Water, per cent by weight of Dry Material.			Ratio of Water to Volume of Cement.							
		Mortar.			Mortar.			Concrete.				
Ref. No.	Fineness Residue on No. 200 Sieve.	Neat.[1]	1:3 St'd.	1:3 Elgin.	Neat.[1]	1:3 St'd.	1:3 Elgin.	1:1½:3	1:1¾:3½	1:2:4	1:2½:5	1:3:6
F-1.....	4.9	29.0	11.3	12.3	0.40	0.62	0.68	0.64	0.68	0.75	0.84	0.99
F-2.....	8.7	28.0	11.2	12.2	0.41	0.65	0.71	0.67	0.73	0.78	0.88	1.06
F-3.....	14.2	27.5	11.1	12.1	0.42	0.68	0.74	0.71	0.76	0.83	0.93	1.12
F-4.....	17.9	26.0	10.8	11.8	0.41	0.68	0.74	0.72	0.78	0.84	0.95	1.14
F-5.....	24.5	25.0	10.7	11.7	0.40	0.69	0.75	0.74	0.80	0.86	0.99	1.15
F-6.....	28.1	24.5	10.6	11.6	0.39	0.68	0.75	0.74	0.81	0.88	1.00	1.18
F-7.....	33.4	24.0	10.5	11.5	0.39	0.69	0.75	0.75	0.82	0.89	1.03	1.19
G-1.....	2.2	29.0	11.3	12.3	0.38	0.59	0.64	0.61	0.65	0.70	1.00	0.94
G-2.....	7.9	26.0	10.8	11.8	0.37	0.62	0.68	0.67	0.71	0.76	0.89	1.05
G-3.....	12.9	25.0	10.7	11.7	0.38	0.65	0.71	0.70	0.75	0.80	0.94	1.10
G-4.....	19.9	25.0	10.7	11.7	0.40	0.68	0.74	0.73	0.78	0.84	0.98	1.15
G-5.....	25.2	24.5	10.6	11.6	0.39	0.68	0.75	0.74	0.80	0.86	1.01	1.18
G-6.....	29.5	24.5	10.6	11.6	0.40	0.69	0.76	0.75	0.81	0.86	1.02	1.19
G-7.....	34.0	24.0	10.5	11.5	0.39	0.69	0.75	0.75	0.81	0.87	1.03	1.19
H-1.....	12.0	23.0	10.3	11.3	0.35	0.62	0.68	0.68	0.73	0.80	0.93	1.08
H-2.....	19.9	23.0	10.3	11.3	0.36	0.65	0.71	0.71	0.76	0.84	0.98	1.15
H-3.....	23.3	21.5	10.1	11.1	0.34	0.65	0.71	0.72	0.78	0.85	0.99	1.16
H-4.....	25.1	22.0	10.2	11.2	0.35	0.66	0.72	0.73	0.78	0.86	1.01	1.18
H-5.....	30.1	22.0	10.2	11.2	0.36	0.66	0.73	0.74	0.79	0.86	1.02	1.19

[1] Normal consistency of cement.

For cements K and L used in Series 118 and 120 mechanical analyses were made by means of the air analyzer shown in Fig. 3. This apparatus was constructed on the same general principles followed in the analyzer designed by the Bureau of Standards, described in *Technologic Paper No. 48,* 1915. Our apparatus differs from the earlier analyzer in several important particulars:

1. Four separations may be made at once using the same air supply, and stacks and nozzles of different diameters;
2. The nozzles and stacks are of brass instead of glass;
3. The nozzles are fixed with reference to the stack;
4. The glass bulb is smaller and simpler in form.

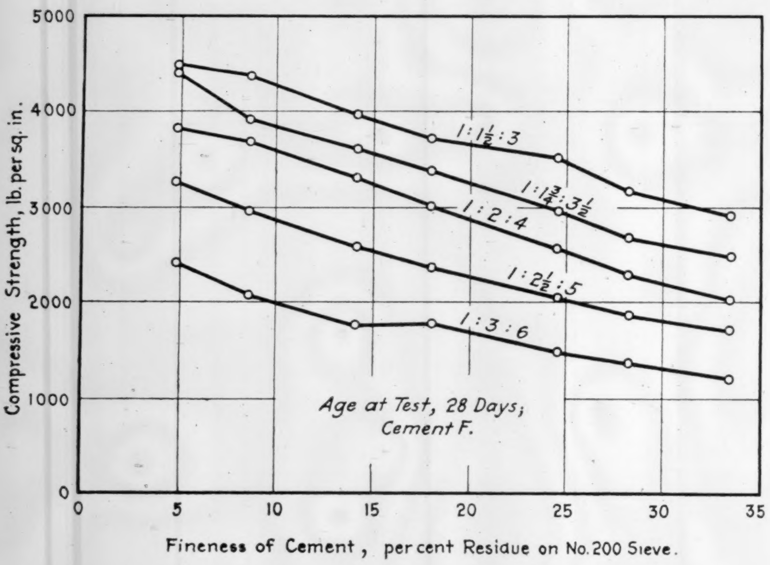

FIG. 8.—Effect of Fineness of Cement on the Strength of Concrete—Series 31.

Compression tests of 6 by 12-in cylinders. See Table XIV.

All stacks were 61 in. in length. Other dimensions are as follows:

UNIT.	INSIDE DIAMETER OF STACK, IN.	NOZZLE DIAMETER, IN.
A	2.62	0.130
B	2.86	0.100
C	3.12	0.070
D	3.37	0.040

Fifty-gram samples were used for Units A, B and C and 25-gram samples for Unit D. An air pressure of 1 lb. per sq. in. was used. The separation size of the units and the analyses of the cements are given in Table V.

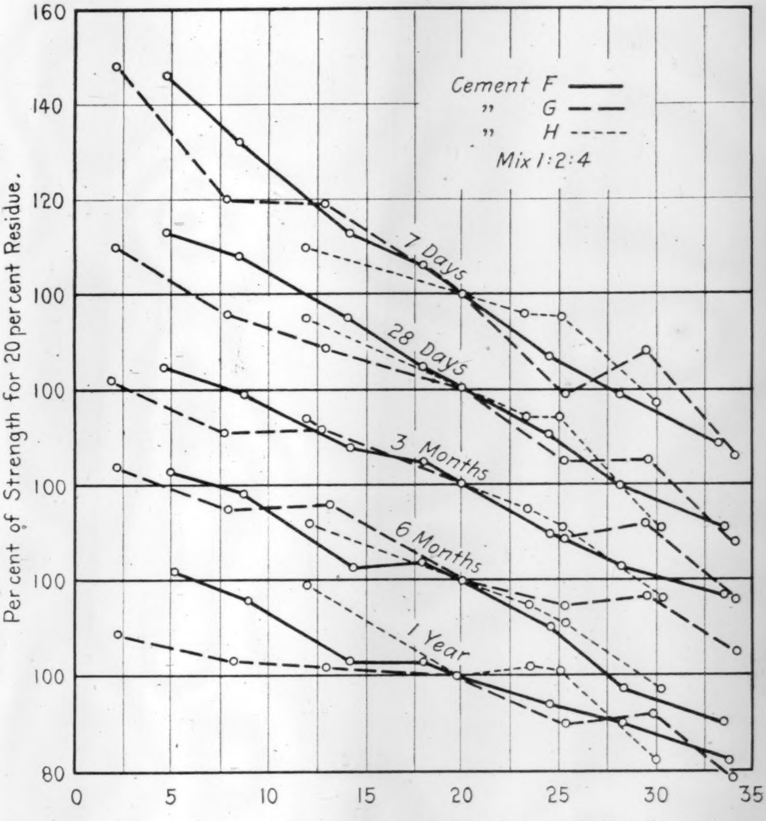

FIG. 9.—Effect of Fineness of Cement on the Strength of Concrete—Series 31.

Compression tests of 6 by 12-in. cylinders. See Table XIV. Compare Fig. 18.

The unit weights of the cement and aggregate were determined by puddling the material in a machined-cast-iron measure in the manner described above for molding the concrete test pieces. The cast-iron measures were cylindrical in form with inside diameter equal to depth. In general, a $\frac{1}{5}$ cu. ft. measure was used.

The compression tests of mortar cylinders were made in a 40,000-lb. Riehlé testing machine. The tests of 6 by 12-in. concrete cylinders were made in a 200,000-lb. Olsen machine. A spherical bearing block was used on top of the compression specimens during the test.

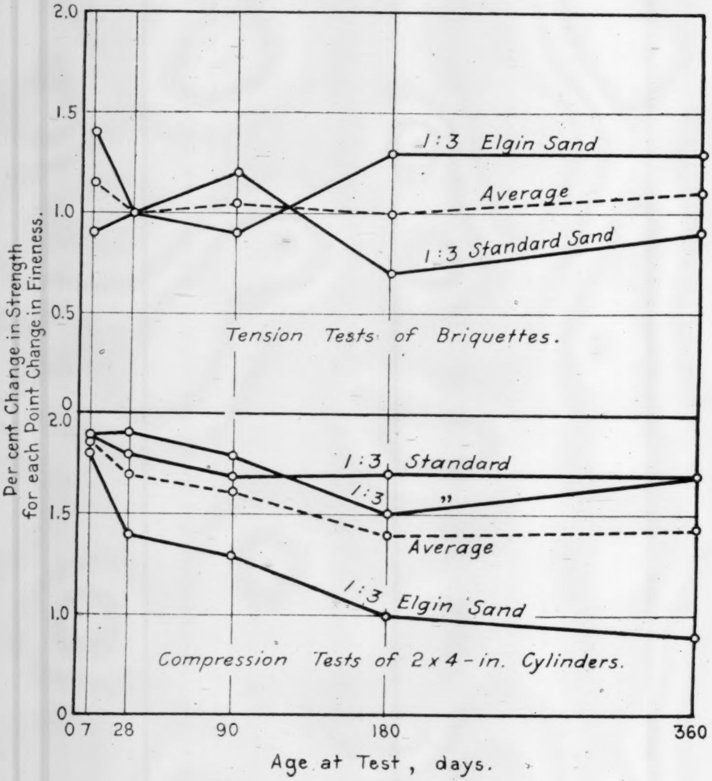

FIG. 10.—Change in Strength of Mortar with Fineness of Cement—Series 31.

Compare Figs. 5 and 6.

Each value is based on 95 tests; cements F, G and H.

A special apparatus (Fig. 4) was designed and constructed for use in measuring the elongation and contraction of 6 by 12-in. cylinders. It consists essentially of a framework for holding the cylinder in an inclined position in V-shaped seats and means for accurate measurement of changes in length. The lower end of the cylinder rests against a 2-in. circular plate with a spherical seat. The change in length is measured by means of an Ames dial graduated to 0.001 in., which makes contact with the cylinder through a second 2-in. plate with spherical seat.

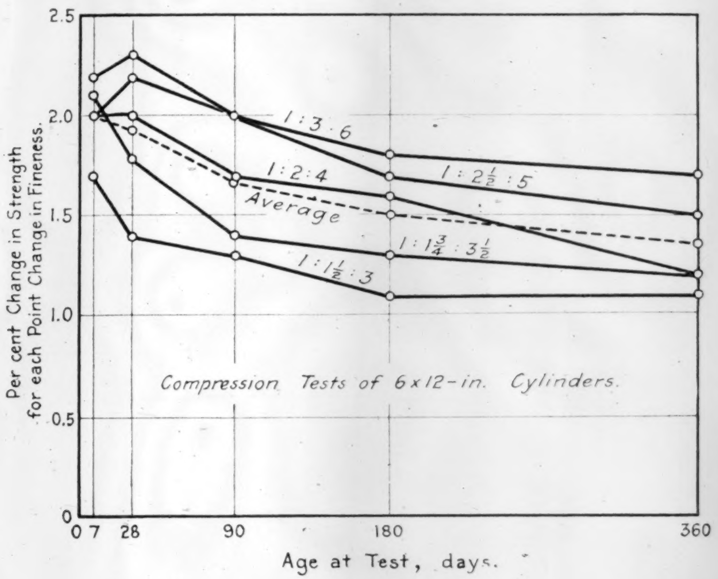

FIG. 11.—Change in Strength of Concrete with Fineness of Cement—Series 31.

Compare Fig. 7.
Each value is based on 95 tests; cements F, G and H.

DISCUSSION OF TESTS.

The data of all tests referred to are given in the tables and diagrams. The data for each series are placed in a group for convenience of reference.

In this discussion most weight will be given to the compres-

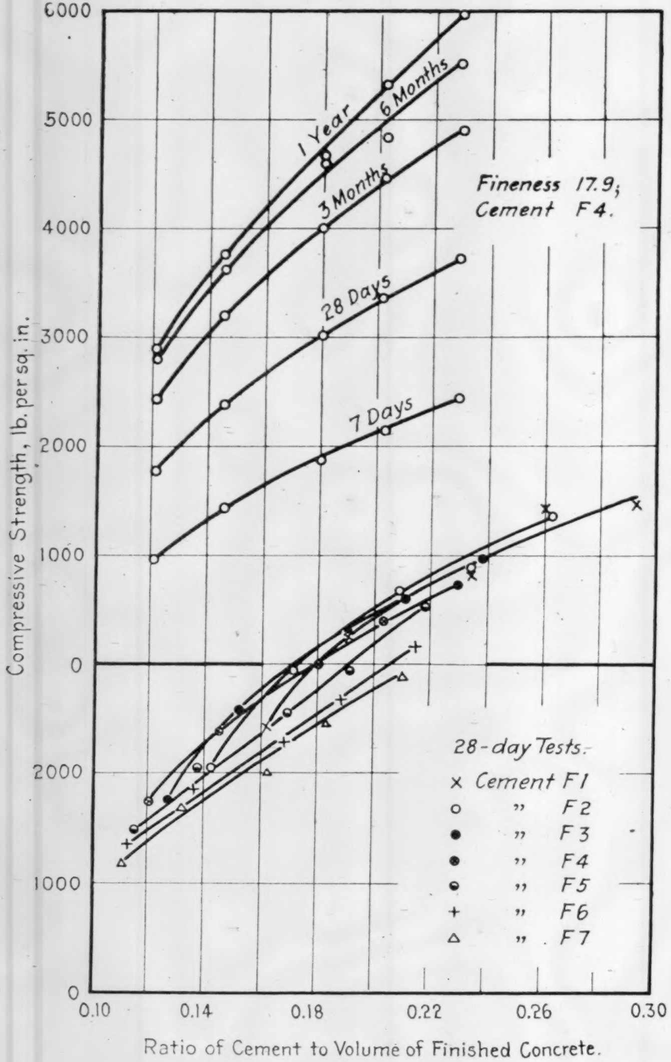

FIG. 12.—Effect of Quantity of Cement on the Strength of Concrete —Series 31.

Compression tests of 6 by 12-in. cylinders. Data from Table XIV.

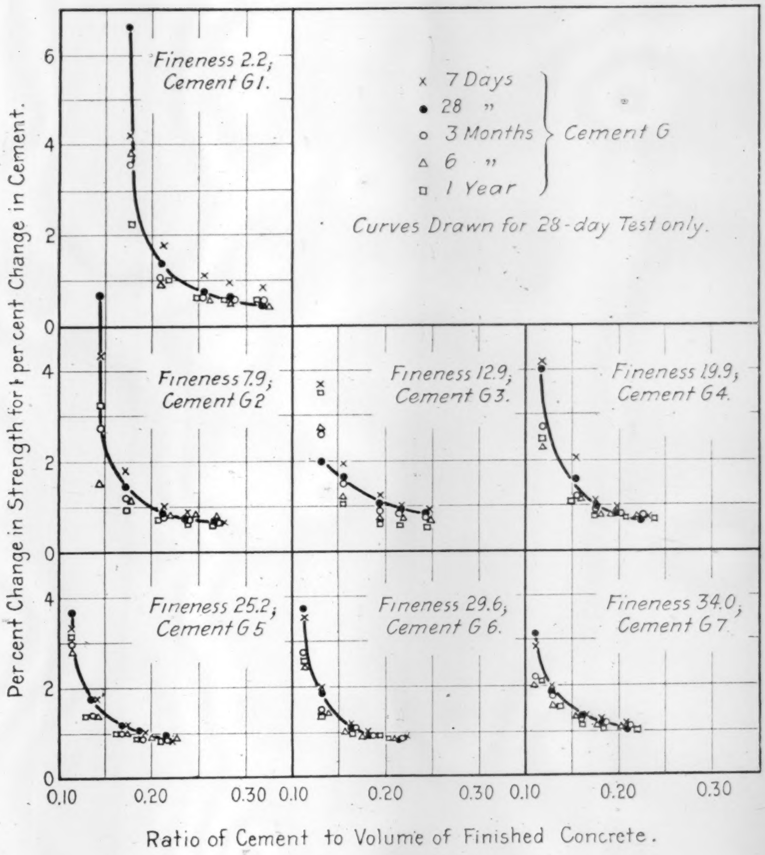

FIG. 13.—Rate of Change in Strength of Concrete with Quantity of Cement—Series 31.

Compression tests of 6 by 12-in. cylinders. Cement G. Compare Figs. 14 and 36. Values determined from curves similar to those in Fig. 12.

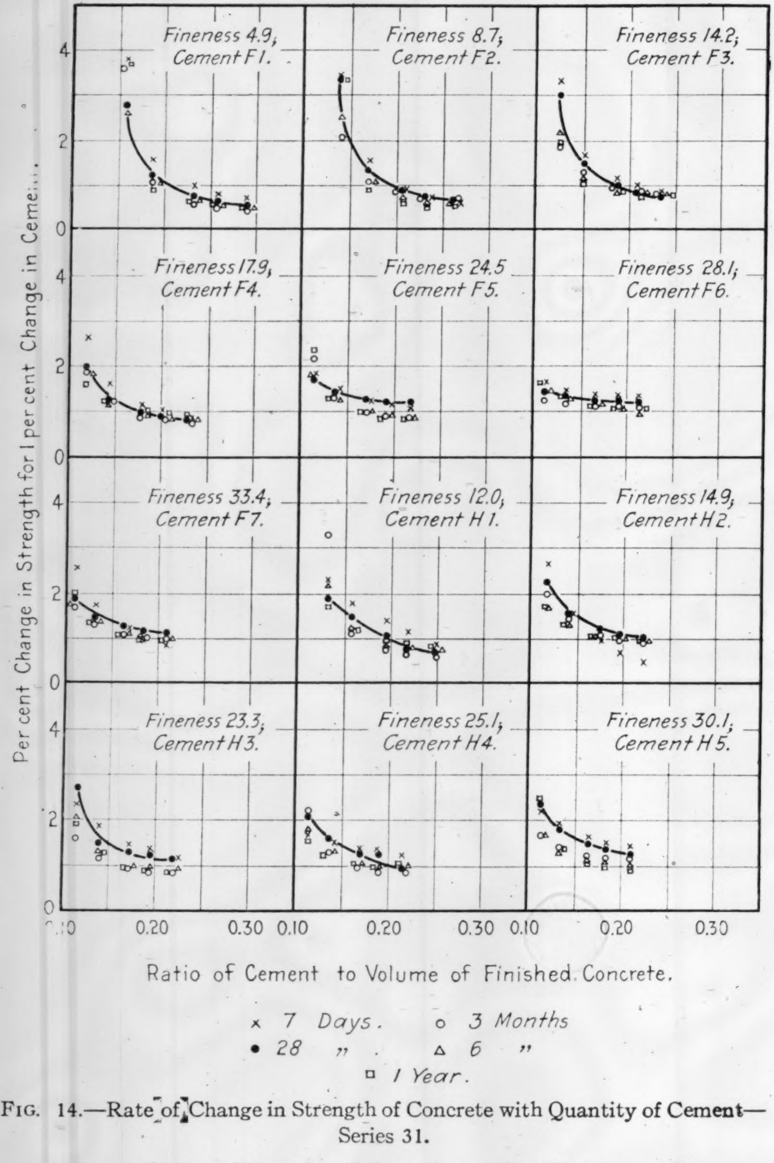

FIG. 14.—Rate of Change in Strength of Concrete with Quantity of Cement—Series 31.

Compression tests of 6 by 12-in. cylinders. Cements F and H. **Compare Figs. 13 and 36.**

Curves drawn for 28-day tests only.

Values determined from curves similar to those in Fig. 12.

sion tests of 6 by 12-in. cylinders. Tests of this kind were made in each series with the exception of No. 60. The results are given in Tables X, XIV, XVIII, XXIII, XXIV and XXVI. This report contains such a mass of data that the discussion will necessarily

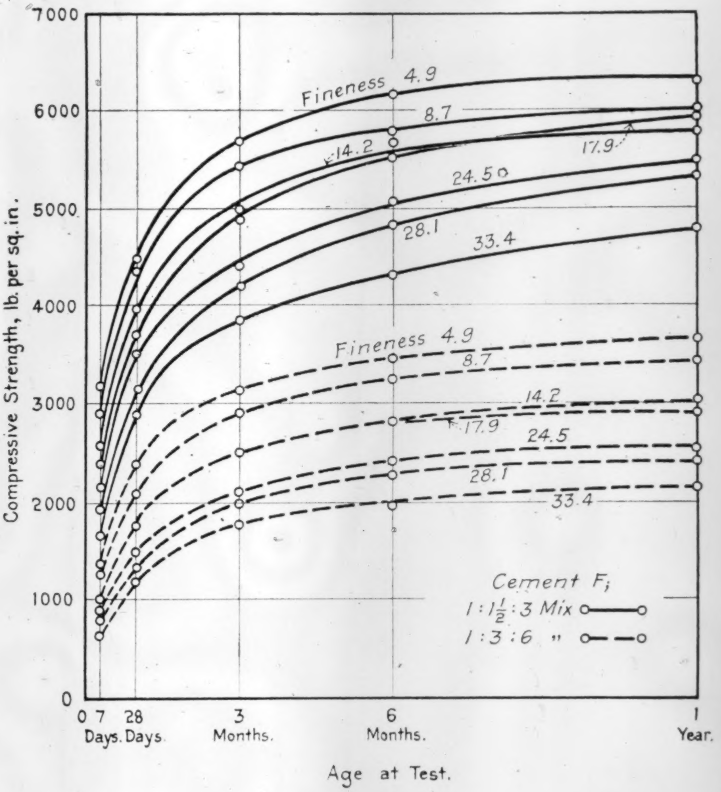

FIG. 15.—Effect of Age on the Strength of Concrete—Series 31.

Compression tests of 6 by 12-in. cylinders. See Table XIV.

be confined to the more important features. The reader who is interested in certain details will find all necessary data for a more thorough study.

Effect of Fineness of Cement on the Strength of Concrete.—An examination of the tables and figures indicates that in general

TABLE XVI.—EFFECT OF FINENESS OF CEMENT ON STRENGTH OF MORTAR—SERIES 60.

2 by 4-in. cylinders; stored in water; tested wet. Mix 1:2.55 by volume. Sand from Elgin, Ill. Each value is the average of 5 tests made on different days.

Cement.			Water per cent by weight.	Compressive Strength, lb. per sq. in.					Relative Strength of Mortar.				
Ref. No.	Fineness Residue on No. 200 Sieve.	Normal Consistency.		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
SAND N-14. FINENESS MODULUS 4.44.													
F-1	4.9	26.0	10.5	4360	5920	6960	7280	8340	108	103	101	96	97
F-2	8.7	26.0	10.5	4480	6100	7120	7430	8070	111	107	103	98	93
F-3	14.2	24.5	10.2	4150	5810	6840	7280	8280	102	101	99	96	96
F-4	17.9	24.0	10.1	4130	5870	7000	7820	8820	102	103	102	103	102
F-5	24.5	23.0	9.9	3870	5420	6610	7030	8200	96	95	96	92	95
F-6	28.1	22.0	9.7	3350	4890	5890	6430	7520	83	85	86	84	87
F-7	33.4	22.0	9.7	3180	4560	5810	5840	7370	79	80	85	77	85
Average	....	......	10.1	3930	5510	6600	7020	8080					
SAND N-10. FINENESS MODULUS 4.06.													
F-1	4.9	26.0	10.9	4030	5790	6420	7120	8500	112	112	104	99	111
F-2	8.7	26.0	10.9	3890	5640	6320	7340	8030	108	109	102	103	105
F-3	14.2	24.5	10.6	3960	5330	6200	6410	8060	110	103	100	90	105
F-4	17.9	24.0	10.5	3730	5390	6490	7420	7990	104	103	105	105	104
F-5	24.5	23.0	10.2	3300	4860	5570	6660	6910	92	94	90	93	90
F-6	28.1	22.0	10.0	2690	4300	5620	5880	6530	75	83	91	82	85
F-7	33.4	22.0	10.0	2570	4100	4970	5320	6560	71	79	80	84	86
Average	....	......	10.4	3400	5040	5940	6590	7510					
SAND N-7. FINENESS MODULUS 3.63.													
F-1	4.9	26.0	11.3	3660	5080	6260	6860	7550	118	112	109	116	104
F-2	8.7	26.0	11.3	3380	4890	6180	6520	7170	109	108	108	111	99
F-3	14.2	24.5	11.0	3300	4830	5760	6060	6800	107	106	101	103	94
F-4	17.9	24.0	10.9	3190	4820	5930	6080	7480	103	106	103	103	103
F-5	24.5	23.0	10.7	2900	3930	5310	5520	6750	94	87	93	93	93
F-6	28.1	22.0	10.5	2210	3560	4370	5360	5730	71	78	76	91	79
F-7	33.4	22.0	10.5	2290	3370	4340	4780	5260	74	74	76	81	73
Average	....	....	10.9	2990	4350	5450	5880	6680					
SAND N-5. FINENESS MODULUS 3.17.													
F-1	4.9	26.0	11.9	3020	4470	5400	5850	6650	120	118	110	110	104
F-2	8.7	26.0	11.9	2890	4150	5480	6280	7110	115	109	112	118	112
F-3	14.2	24.5	11.6	2640	4070	5160	6040	6340	105	107	105	114	99
F-4	17.9	24.0	11.5	2660	3980	5230	5540	6690	106	105	107	104	105
F-5	24.5	23.0	11.3	2200	3420	4230	4820	5680	88	90	86	91	89
F-6	28.1	22.0	11.1	1790	2980	3960	4400	4860	71	78	81	83	76
F-7	33.4	22.0	11.1	1640	2760	3310	3690	4380	65	73	68	70	69
Average	....	....	11.5	2410	3690	4680	5230	5960					

TABLE XVI—*Continued.*

Cement.			Water per cent by weight.	Compressive Strength, lb. per sq. in;					Relative Strength of Mortar.				
Ref. No.	Fineness Residue on No. 200 Sieve.	Normal Consistency.		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
SAND N-S. FINENESS MODULUS 3.00.													
F-1.....	4.9	26.0	12.3	3200	4750	5570	5800	6510	136	131	125	121	119
F-2.....	8.7	26.0	12.3	2840	4470	5610	5730	5910	121	123	126	119	108
F-3.....	14.2	24.5	12.0	2580	3920	4810	5020	5700	109	108	108	105	104
F-4.....	17.9	24.0	11.9	2470	3910	4700	5060	5720	105	108	105	106	105
F-5.....	24.5	23.0	11.7	2110	3040	3950	4290	4980	89	84	89	89	91
F-6.....	28.1	22.0	11.5	1670	2690	3480	3770	4330	71	74	78	78	79
F-7.....	33.4	22.0	11.5	1730	2500	3140	3410	4330	73	69	71	71	79
Average	....	....	11.9	2370	3610	4470	4730	5350					
SAND N-3. FINENESS MODULUS 2.53.													
F-1.....	4.9	26.0	12.8	2460	3930	4680	5400	6330	140	137	130	134	140
F-2.....	8.7	26.0	12.8	2370	3630	4750	5020	6010	135	127	132	125	133
F-3.....	14.2	24.5	12.5	2080	3250	3970	4520	5240	118	113	110	112	116
F-4.....	17.9	24.0	12.4	1810	3070	3830	4190	4960	103	107	106	103	109
F-5.....	24.5	23.0	12.1	1650	2420	3100	3630	3620	94	84	86	91	80
F-6.....	28.1	22.0	12.0	1360	2020	2800	3020	3900	77	70	78	75	86
F-7.....	33.4	22.0	12.0	1370	1920	2840	2860	3350	78	67	79	71	74
Average	....	......	12.4	1870	2890	3710	4090	4770					

the strength of concrete increases with the fineness of cement. There are notable exceptions to this rule in the case of some of the cements having residues less than about 10 per cent on the No. 200 sieve.

The rate of change of strength of concrete with the fineness of the cement may be studied in several different ways. One method is illustrated in Fig. 8 where the strength of the concrete for different mixtures has been platted against the fineness of the cement. In this instance only cement F was platted; the other cements in this group give similar relations. It will be seen that the relation between the strength and fineness for the range of values covered may be represented by straight lines, which may be used to determine the percentage change in strength for one fineness of cement as compared with another. In all of our calculations we have used the strength found for residue of 20 per cent as a basis of comparison. It will be seen that the percentage increase in strength for 1 per cent reduction in residue is considerably greater for the lean than for the rich mixtures.

Fig. 9 gives data similar to that found in Fig. 8 except that the values have been reduced to basis of 100 per cent for a residue of 20 per cent and the curves for cements G and H have been added. While there is a wide variation in the fineness covered by these cements, it will be noted that the values give roughly a straight-line relation. The slopes of the curves for cement F are in general higher than the average, cement G is lower than the average, and cement H is about a mean between the other

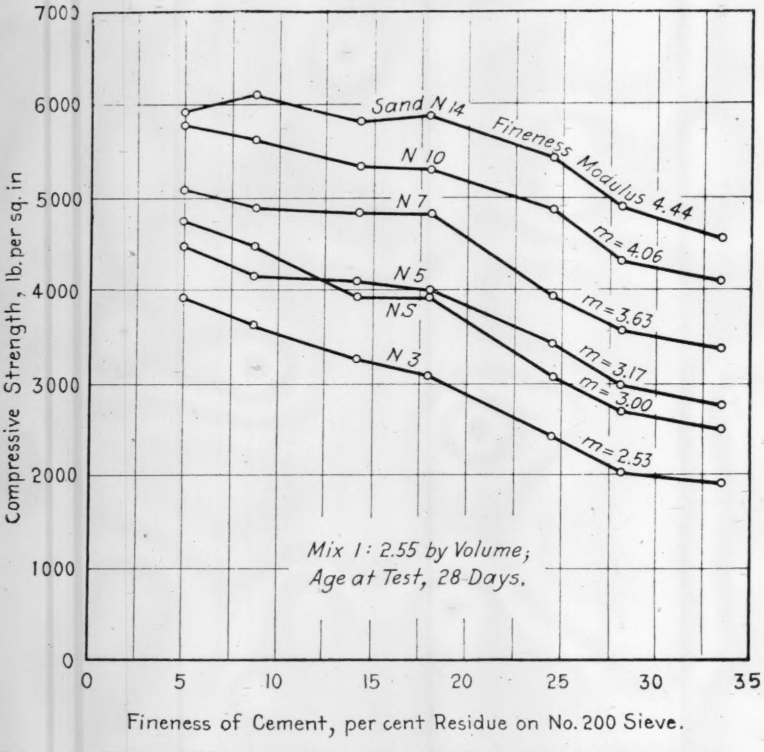

FIG. 16.—Effect of Fineness of Cement on the Strength of Mortar—Series 60.

Compression tests of 2 by 4-in. cylinders. See Table XVI.
Curves platted for 28-day tests only.

two. The slopes of the curves at 7 days are much greater than for other periods, indicating that finer grinding of the cement is more effective in increasing the early strength of the concrete than at subsequent periods. Similar diagrams for mortar tests made of sand of six different gradings at ages ranging from 7 days to 1 year are given in Figs. 16 to 18.

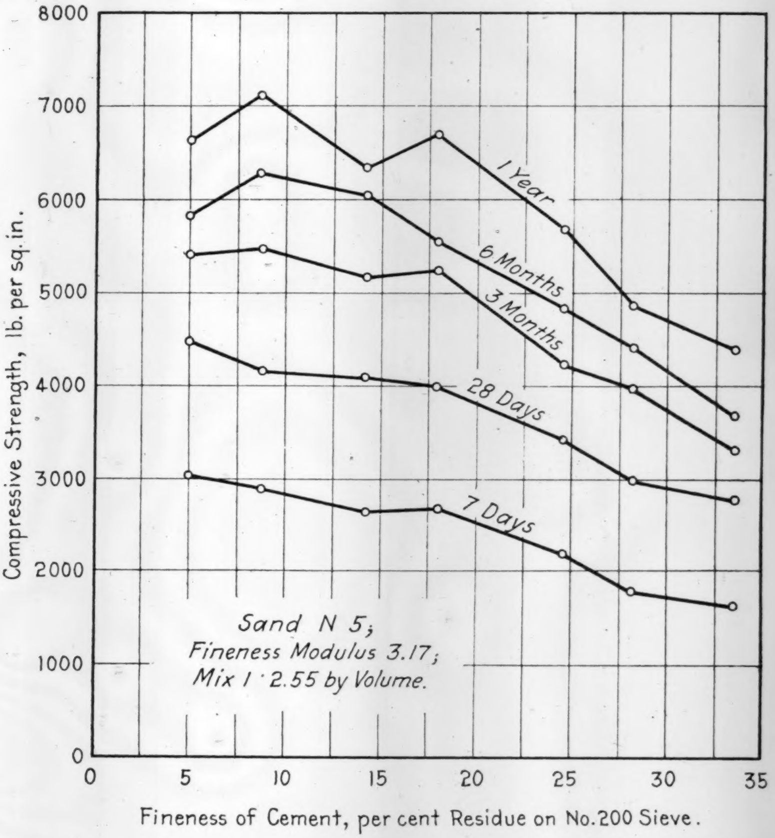

FIG. 17.—Effect of Fineness of Cement on the Strength of Mortar—Series 60.

Compression tests of 2 by 4-in. cylinders. See Table XVI.
Curves platted for Sand N-5 only.

The relation between the strength of concrete and fineness of cement for cements K and L in Series 118 and 120 is found in Figs. 21, 22, 23, 25 to 29. It will be noted that for all conditions of consistency, mix and size of aggregates the strength for cement K falls off for the finest sample. The linear relation between fineness and strength is correct only for residues above 10 per cent for this cement.

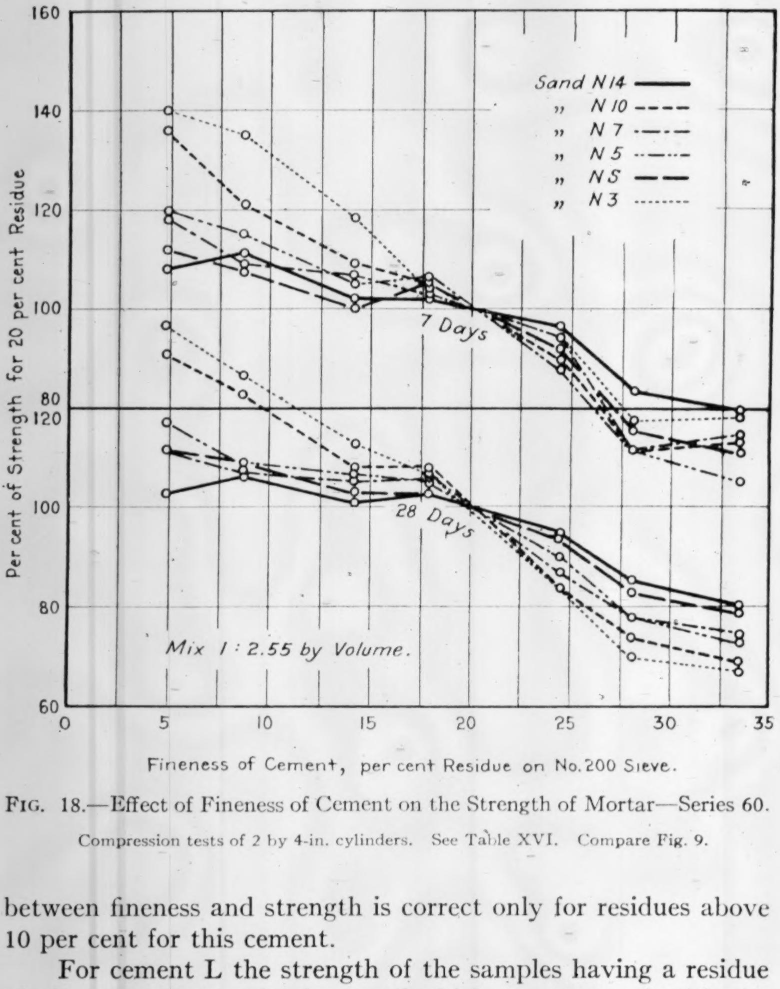

FIG. 18.—Effect of Fineness of Cement on the Strength of Mortar—Series 60.

Compression tests of 2 by 4-in. cylinders. See Table XVI. Compare Fig. 9.

For cement L the strength of the samples having a residue of about 7 per cent is abnormally high as compared with the other finenesses (see Fig. 29). These tests indicate that the

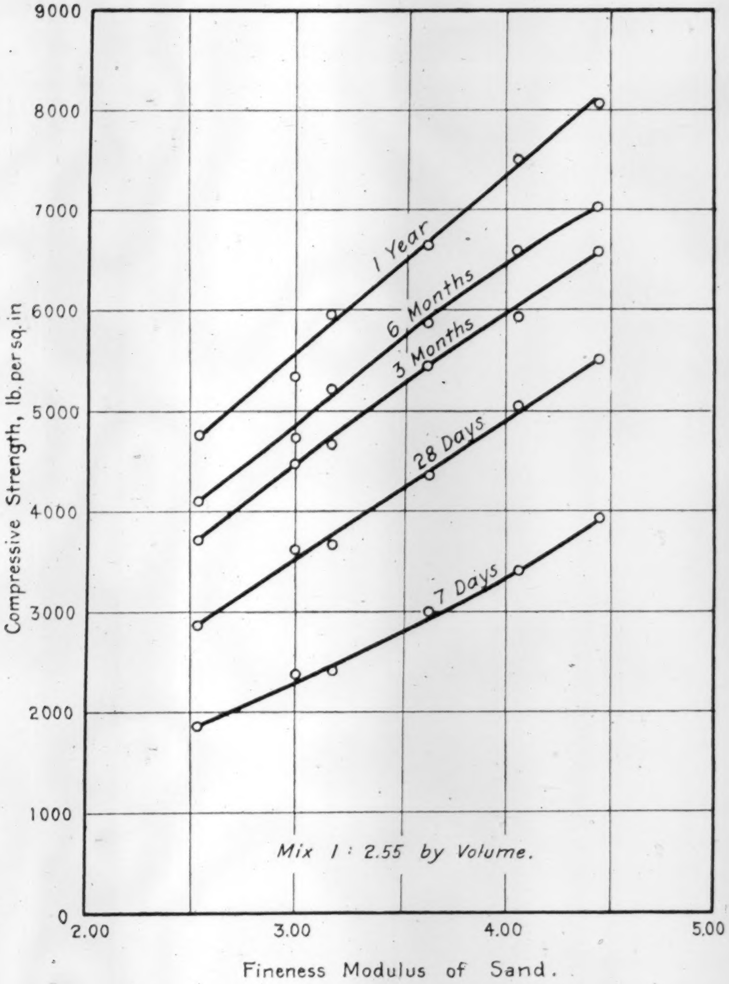

FIG. 19.—Effect of Grading of Sand on the Strength of Mortar—Series 60.

Compression tests of 2 by 4-in. cylinders. See Table XVI. Compare Fig. 34. Values are the average of 35 tests from 7 finenesses of Cement F.

extremely fine cements are likely to be erratic in their behavior. It will be pointed out below that the time of setting and the mortar strengths of the finest cements are also erratic.

TABLE XVII.—STRENGTH TESTS OF CEMENTS—SERIES 118 AND 120.

Mortar specimens were mixed to the consistency required by the standard specifications and methods of test of the American Society for Testing Materials.

Neat cement tests were made on paste of normal consistency.

Specimens stored in water; tested damp.

Each value is the average of 5 tests made on different days.

One-year tests in this series not yet due.

Cement.		2 by 4-in. Cylinders, Compressive Strength, lb. per sq. in.				Briquettes, Tensile Strength, lb. per sq. in.			
Ref. No.	Fineness Residue on No. 200 sieve.	3 d.	7 d.	28 d.	3 mo.	3 d.	7 d.	28 d.	3 mo.
1:3 STANDARD SAND MORTAR.									
I-1.....	8.9	....	900	2880	3760	....	158	268	401
I-2.....	13.9	....	810	1730	3030	....	175	250	341
Average	....	....	860	2300	3400	....	166	259	371
K-1.....	2.4	1630	2110	3370	4430	222	275	370	427
K-2.....	9.4	1270	2270	3680	4290	195	261	360	395
K-3.....	17.7	980	1520	2840	3430	160	228	331	380
K-4.....	27.9	680	1050	1840	2810	89	112	254	345
K-5.....	36.2	320	780	1390	1590	40	65	190	295
Average.	....	980	1550	2620	3310	141	188	301	368
L-1.....	7.1	740	1640	3090	4400	121	204	385	458
L-2.....	16.3	540	1220	2670	3100	81	184	317	327
L-3.....	28.9	250	680	1280	1770	65	104	227	276
L-4.....	32.3	200	460	1190	1450	42	63	170	278
L-5.....	43.3	170	350	610	1250	37	60	213	185
Average.	....	380	870	1770	2390	69	123	262	305
NEAT CEMENT.									
K-1.....	2.4	5030	6800	9470	9210	486	600	551	558
K-2.....	9.4	7000	8180	12470	12380	594	573	600	623
K-3.....	17.7	5800	8950	12580	12830	440	617	612	682
K-4.....	27.9	3740	6730	10880	11800	380	555	521	674
K-5.....	36.2	1540	5050	9240	10390	185	530	673	698
Average.	....	4620	7140	10930	11320	417	575	591	647
L-1.....	7.1	4600	7150	11560	12900	334	423	582	455
L-2.....	16.3	3600	5890	9120	11010	358	416	605	564
L-3.....	28.9	1950	3940	7330	10140	224	333	582	671
L-4.....	32.3	1510	3480	6950	9080	202	321	601	559
L-5.....	43.3	1340	2740	6000	9450	180	261	601	664
Average.	....	2600	4640	6190	10520	260	351	594	583

The most useful basis for comparison in studying the effect of fineness of cement is the percentage increase in strength of the concrete for 1 per cent reduction in residue of the cement on the No. 200 sieve. The values calculated from the slopes of the curves may be found for Series 20 and 31 in Figs. 7 and 11, and for Series 118 and 120, in Tables XX, XXVIII and XXIX.

TABLE XVIII.—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 118.

Compression tests of 6 by 12-in. cylinders.
Mix by volume.
Age at test, 28 days.
Specimens stored in damp sand; tested damp.
Each value is the average of 3 or 5 tests made on different days.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.

Ref. No.	Cement. Fineness, Residue on No. 200 sieve.	Compressive Strength, lb. per sq. in. for Different Consistencies.									
		0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
AGGREGATE, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1	8.5	3670	4020	3330	3120	2890	2600	2160	1220	....	2880
I-2	13.9	3140	3120	2880	1940	2170	1350	1690	1320	....	2310
Average		3400	3570	3100	2530	2530	1980	1920	1270	....	2600
AGGREGATE, SAND AND PEBBLES—MIX 1:4.											
K-1	2.4	3240	2940	3200	3290	3030	3070	2580	1890	960	2690
K-2	9.4	3900	4020	3860	3630	3020	3290	2830	2100	1040	3080
K-3	17.7	3410	3690	3620	3270	2970	2490	2470	1610	1020	2730
K-4	27.9	2030	2420	2380	2050	1930	1920	1650	1210	820	1820
K-5	36.2	1360	1430	1640	1530	1500	1260	1310	1010	660	1300
Average		2790	2900	2940	2750	2490	2410	2170	1560	900	2320
AGGREGATE, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG—MIX 1:1¾.											
K-1	2.4	4780	4960	4800	4570	4290	4190	3910	2750	1600	3980
K-2	9.4	5070	4520	4840	4770	4800	4410	4270	3250	1740	4180
K-3	17.7	4240	4550	4700	4250	4060	4010	3840	3040	1540	3800
K-4	27.9	2730	3230	3210	3220	2770	2930	2680	1980	900	2630
K-5	36.2	2180	3130	2820	2580	2500	2580	2100	1520	810	2250
Average		3800	4080	4070	3880	3690	3620	3360	2510	1320	3370
L-1	7.1	3340	3320	3620	3300	3150	2620	2580	1760	910	2730
L-2	16.3	2600	3000	2760	2530	2350	2200	2270	1490	760	2220
L-3	28.9	1470	1990	2710	2550	2340	1940	2040	1310	700	1890
L-4	32.3	1180	1900	1930	2010	1810	1780	1790	1120	690	1580
L-5	43.3	1060	1380	1660	1610	1570	1460	1200	850	500	1250
Average		1930	2320	2540	2400	2240	2000	1980	1310	710	1930

The tests show that the lean mixtures are increased in strength relatively more than the rich ones for a given change in the fineness of the cement. They also show that the beneficial effect of fine grinding tends to disappear with the age of the concrete.

The values in Tables XX and XXVIII in which a wide range in consistencies was used, indicate that the change in strength due to fineness of cement is largely independent of the consistency of the concrete. An exception to this rule is found in the case of the very wet mixtures (relative consistency 2.00) where the rate of increase in strength was considerably lower than the average.

TABLE XIX.—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 118.

Strength tests given in Table XVIII.

Water reported on basis of true volume of cement, that is, the differences in unit weights of the cements are taken into account. The quantity of mixing water for a given mix and consistency would be constant were it not for (1) different normal consistencies in the cement and (2) different unit weights of cement.

Cement.		Ratio of Water to Volume of Cement for Different Consistencies.								
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.										
I-1....	8.5	0.676	0.712	0.748	0.783	0.819	0.855	0.891	1.070	.....
I-2....	13.9	0.705	0.742	0.777	0.815	0.852	0.890	0.927	1.112	.....
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.										
K-1...	2.4	0.644	0.675	0.712	0.744	0.778	0.814	0.845	1.015	1.353
K-2...	9.4	0.691	0.725	0.763	0.799	0.834	0.872	0.907	1.087	1.450
K-3...	17.7	0.740	0.778	0.817	0.858	0.896	0.933	0.975	1.170	1.558
K-4...	27.9	0.810	0.850	0.896	0.938	0.980	1.024	1.067	1.280	1.704
K-5...	36.2	0.830	0.873	0.916	0.962	1.005	1.048	1.091	1.313	1.748
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG—MIX 1:1¾.										
K-1...	2.4	0.528	0.555	0.584	0.610	0.639	0.668	0.695	0.835	1.113
K-2...	9.4	0.562	0.591	0.620	0.649	0.679	0.710	0.738	0.888	1.183
K-3...	17.7	0.603	0.634	0.664	0.696	0.728	0.758	0.792	0.948	1.268
K-4...	27.9	0.656	0.692	0.727	0.762	0.797	0.832	0.865	1.038	1.383
K-5...	36.2	0.675	0.713	0.748	0.783	0.823	0.855	0.890	1.068	1.428
L-1...	7.1	0.546	0.576	0.603	0.631	0.661	0.689	0.718	0.863	1.148
L-2...	15.3	0.598	0.632	0.662	0.692	0.725	0.755	0.787	0.946	1.260
L-3...	28.9	0.635	0.671	0.705	0.737	0.770	0.807	0.838	1.005	1.340
L-4...	32.3	0.665	0.697	0.730	0.765	0.800	0.835	0.874	1.047	1.390
L-5...	43.3	0.665	0.700	0.733	0.768	0.803	0.837	0.873	1.047	1.400

Effect of Fineness Using Different Cements.—An examination of the tables will show that there is no necessary relation between the fineness of cement and the strength of the resulting concrete so long as different cements are considered. For example, the strengths given by cement L in Series 118 (Table XVIII) are only 40 to 60 per cent of those given by cement K for the same mixtures. The coarsest samples for cement K gave strengths comparable to the finest samples in cement L. It is significant, however, that the rate of change in strength with fineness (Table XX) is not materially different.

Effect of Consistency of Concrete.—Concrete of a wide range in consistency was tested in Series 118 and 120. The effect of consistency on the strength for several mixtures is shown in Fig. 30. Similar diagrams may be constructed for other finenesses of both cements K and L. The strength falls off rapidly as the quantity of mixing water is increased above "normal consistency." For a relative consistency of 1.50 the strength is about one-half the maximum; for relative consistency 2.00, only 25 to 40 per cent of the maximum. In general, the strength falls off for mixtures drier than relative consistency 1.00. The richer mixtures are more affected by increase in water than the lean ones. These tests confirm the results of earlier investigations made in this Laboratory.

TABLE XX.—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 118.

(EFFECT OF CONSISTENCY.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Table XVIII.)

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentages shown.

No attempt was made to calculate values for Cement I, since the two samples were not from the same lot and gave a narrow range in fineness.

Cement.	Mix by Volume.	Age at Test, days.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per cent of Strength for 20 per cent Residue.									
			0.95[a]	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.												
K......	1:4	28	3.3	3.5	3.1	3.1	2.7	2.7	2.7	2.5	2.1	2.9
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURANCE SLAG.												
K.......	1:1¾	28	3.0	1.8	2.3	2.0	2.7	2.2	2.1	2.8	2.8	2.4
L.......	1:1¾	28	3.3	2.2	2.1	1.8	1.7	1.4	2.0	2.1	1.3	1.9
Grand Average.............			3.2	2.5	2.5	2.3	2.4	2.1	2.3	2.5	2.1	2.4

[a] Relative consistency of concrete.

The water-ratio has been found convenient as a method of dealing with the relation between the water content and strength of concrete. The water-ratio is the ratio of the volume of water to the volume of cement in the batch. Our investigations indicate that this ratio may be used as a measure of the strength of concrete for given materials and given test conditions, regardless of the mix, size or grading of the aggregate, or the relative

TABLE XXI.—SLUMP TESTS FOR WORKABILITY OF CONCRETE—SERIES 118.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Each value is the average of 3 or 5 tests made on different days.

Cement.		Slump for Different Consistencies, in.								
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	Average.
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.										
I-1...	8.5	0.4	1.4	2.3	3.3	4.7	7.0	7.3	10.1	4.3
I-2...	13.9	0.6	1.6	3.6	6.2	7.7	8.7	9.0	10.7	5.8
Average.........		0.5	1.5	3.0	4.8	6.2	7.8	8.2	10.4	5.0
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.										
K-1...	2.4	0.8	1.3	3.7	5.8	7.1	8.3	9.0	10.1	5.8
K-2...	9.4	0.7	1.8	4.7	7.2	8.5	8.4	8.8	9.8	6.2
K-3...	17.7	0.4	0.8	2.4	6.9	7.7	8.1	8.6	9.7	5.6
K-4...	27.9	0.2	0.4	1.2	5.9	7.7	7.4	8.1	9.2	5.0
K-5...	36.2	0.2	0.3	0.4	0.7	2.3	6.4	7.1	8.9	3.3
Average.........		0.5	0.9	2.5	5.3	6.7	7.7	8.3	9.5	5.2
AGGREGATES, CELITE, SAND AND CRUSHED BLAST FURNACE SLAG—MIX 1:1¾.										
K-1...	2.4	0.4	0.9	1.6	3.2	4.1	5.7	6.9	9.6	4.0
K-2...	9.4	0.5	0.9	2.0	3.3	4.9	6.9	7.9	10.5	4.6
K-3...	17.7	0.4	0.7	1.6	3.4	5.2	7.2	8.0	10.2	4.6
K-4...	27.9	0.3	0.7	1.3	3.1	5.3	6.9	7.8	10.1	4.4
K-5...	36.2	0.3	0.8	1.2	2.3	4.9	6.6	7.7	10.1	4.2
Average.........		0.4	0.8	1.5	3.1	4.9	6.7	7.7	10.1	4.4
L-1...	7.1	0.4	0.9	2.2	3.3	4.9	6.8	8.4	10.4	4.7
L-2...	15.3	0.3	0.8	1.7	3.1	4.2	6.5	7.2	10.0	4.2
L-3...	28.9	0.2	0.5	0.9	2.6	4.3	6.5	7.5	10.4	4.1
L-4...	32.3	0.2	0.4	0.8	1.3	3.8	6.5	7.1	10.1	3.8
L-5...	43.3	0.2	0.3	0.6	1.2	2.0	5.7	7.0	9.8	3.4
Average.........		0.3	0.6	1.2	2.3	3.8	6.4	7.4	10.1	4.0

consistency of the concrete, so long as the concrete is plastic and the aggregate is not too coarse for the quantity of cement used. Typical examples of the water-ratio - strength relation from these tests may be found in Figs. 31 and 32. Diagrams of the same form may be constructed for the other finenesses from data given in Tables XXIII to XXV. The curves drawn in Fig. 32 were constructed from diagrams similar to Fig. 31 for other finenesses of cement K. It will be noted that a single water-

TABLE XXII*a*.—EFFECT OF FINENESS OF CEMENT ON THE YIELD AND DENSITY OF CONCRETE—SERIES 118.

6 by 12-in cylinders.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 3 or 5 tests made on different days.

Cement.		Relative Consistency of Concrete.									
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50.	2.00	Average.
YIELD OF CONCRETE.											
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1......	8.5	1.322	1.356	1.380	1.405	1.418	1.442	1.439	1.527	......	1.411
I-2......	13.9	......	1.318	1.341	1.363	1.399	1.413	1.411	1.468	......	1.388
Average....................		1.322	1.337	1.360	1.384	1.408	1.427	1.425	1.497		1.399
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.											
K-1.....	2.4	1.079	1.090	1.093	1.106	1.118	1.108	1.127	1.157	1.193	1.119
K-2.....	9.4	1.076	1.080	1.091	1.089	1.093	1.097	1.102	1.130	1.180	1.104
K-3.....	17.7	1.090	1.087	1.083	1.094	1.092	1.104	1.107	1.144	1.178	1.109
K-4.....	27.9	1.127	1.093	1.090	1.103	1.099	1.110	1.115	1.143	1.193	1.119
K-5.....	36.2	1.134	1.121	1.112	1.100	1.113	1.117	1.120	1.149	1.183	1.128
Average....................		1.101	1.094	1.094	1.098	1.103	1.107	1.114	1.145	1.185	1.116
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURANCE SLAG—MIX 1:1¾.											
K-1.....	2.4	1.361	1.350	1.359	1.387	1.396	1.416	1.426	1.503	1.621	1.424
K-2.....	9.4	1.334	1.333	1.332	1.350	1.369	1.378	1.384	1.438	1.570	1.388
K-3.....	17.7	1.332	1.321	1.330	1.347	1.356	1.374	1.382	1.435	1.540	1.380
K-4.....	27.9	1.382	1.350	1.358	1.347	1.354	1.372	1.392	1.453	1.540	1.394
K-5.....	36.2	1.369	1.319	1.357	1.346	1.363	1.372	1.388	1.442	1.550	1.390
Average....................		1.340	1.335	1.347	1.355	1.368	1.382	1.394	1.454	1.564	1.395
L-1.....	7.1	1.363	1.324	1.341	1.350	1.369	1.386	1.394	1.470	1.569	1.396
L-2.....	16.3	1.352	1.321	1.348	1.356	1.364	1.383	1.402	1.444	1.540	1.390
L-3.....	28.9	1.420	1.366	1.344	1.333	1.350	1.379	1.388	1.439	1.543	1.396
L-4.....	32.3	1.440	1.363	1.342	1.340	1.358	1.367	1.385	1.435	1.540	1.397
L-5.....	43.3	1.423	1.359	1.328	1.325	1.333	1.350	1.380	1.437	1.517	1.384
Average....................		1.400	1.347	1.341	1.355	1.355	1.373	1.390	1.445	1.542	1.393

ratio - strength curve in Fig. 31 represents the tests covered by six curves in Fig. 30, except that the low strengths due to abnormally dry concrete have been omitted. The simplicity of the relation brought out in Fig. 31 would not be recognized from a study of the curves in Fig. 30.

TABLE. XXII*b*.—EFFECT OF FINENESS OF CEMENT ON THE YIELD AND DENSITY OF CEMENT—SERIES 118.

Cement.		Relative Consistency of Concrete.									
Ref. No	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
DENSITY OF CONCRETE.											
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1	8.5	0.684	0.667	0.655	0.643	0.637	0.627	0.628	0.592	......	0.642
I-2	13.9	......	0.686	0.674	0.664	0.646	0.640	0.641	0.616	......	0.652
Average		0.684	0.676	0.664	0.653	0.642	0.633	0.634	0.604	......	0.647
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.											
K-1	2.4	0.817	0.808	0.806	0.798	0.789	0.796	0.782	0.762	0.739	0.788
K-2	9.4	0.820	0.816	0.808	0.810	0.806	0.804	0.800	0.780	0.747	0.799
K-3	17.7	0.809	0.812	0.814	0.805	0.807	0.799	0.797	0.770	0.749	0.796
K-4	27.9	0.783	0.807	0.809	0.799	0.803	0.795	0.791	0.772	0.739	0.789
K-5	36.2	0.777	0.787	0.792	0.802	0.792	0.790	0.788	0.768	0.745	0.782
Average		0.801	0.806	0.806	0.803	0.799	0.797	0.792	0.770	0.744	0.791
AGGREGATES, CELITE, SAND AND CRUSHED BLAST FURNACE SLAG—MIX 1:1¾.											
K-1	2.4	0.739	0.745	0.740	0.726	0.721	0.711	0.705	0.669	0.621	0.708
K-2	9.4	0.754	0.755	0.756	0.746	0.735	0.731	0.727	0.700	0.641	0.727
K-3	17.7	0.755	0.762	0.757	0.748	0.743	0.732	0.728	0.702	0.653	0.731
K-4	27.9	0.728	0.745	0.741	0.747	0.743	0.733	0.722	0.692	0.653	0.723
K-5	36.2	0.735	0.753	0.742	0.748	0.738	0.733	0.725	0.698	0.649	0.726
Average		0.742	0.754	0.747	0.743	0.736	0.728	0.721	0.692	0.643	0.723
L-1	7.1	0.739	0.761	0.751	0.746	0.736	0.727	0.722	0.685	0.642	0.723
L-2	16.3	0.743	0.761	0.747	0.742	0.737	0.727	0.717	0.696	0.653	0.725
L-3	28.9	0.708	0.737	0.748	0.755	0.745	0.730	0.725	0.700	0.652	0.722
L-4	32.3	0.699	0.738	0.750	0.752	0.742	0.737	0.727	0.702	0.653	0.722
L-5	43.3	0.707	0.741	0.758	0.759	0.755	0.746	0.729	0.700	0.663	0.729
Average		0.719	0.748	0.751	0.751	0.743	0.733	0.724	0.696	0.652	0.724

The water-ratio - strength relation is of the same form, regardless of the fineness of the cement. The relation may be expressed by an equation of the form,

$$S = \frac{D}{X^a}$$

where S is the compressive strength of the concrete, X is the water-ratio, and *D* and *a* are constants whose values depend on the quality of cement and the conditions of the test. Typical values of the constants *D* and *a* are given in Fig. 32. It should be noted that *a* is an exponent.

Our report on "Design of Concrete Mixtures"[1] gave a somewhat different equation for this relation. For usual ranges of concrete mixtures both forms of equation give similar results; for the wetter consistencies the above equation gives somewhat higher values than the earlier equation. However, it should be understood that the exact type of the algebraic equation is not important. The essential feature is that the water content of the concrete measured in terms of the volume of the cement (the water-ratio) is the determining factor in fixing the strength of concrete made from given materials. In constructing an equation of this kind we are simply deriving the equation of a curve which most nearly represents the experimental values.

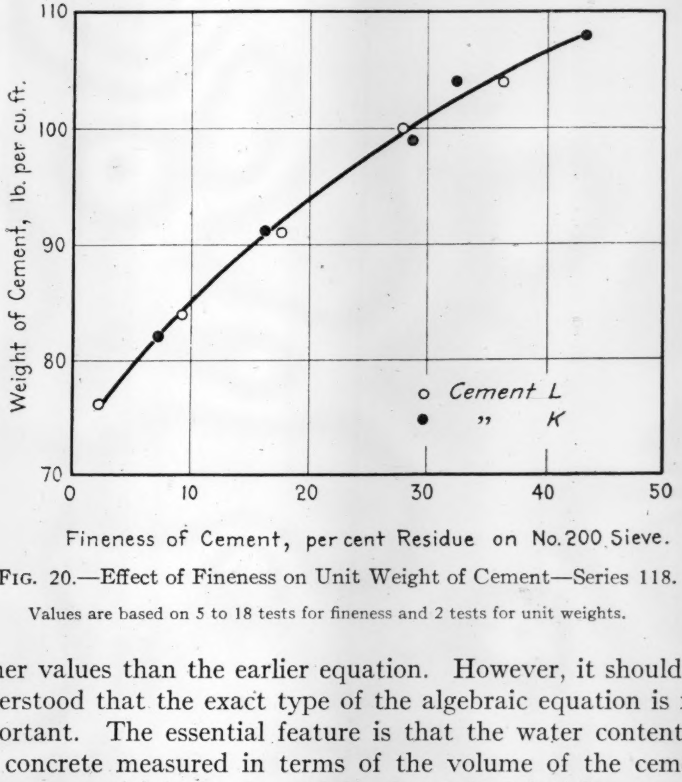

FIG. 20.—Effect of Fineness on Unit Weight of Cement—Series 118.

Values are based on 5 to 18 tests for fineness and 2 tests for unit weights.

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[1] *Bulletin No. 1*, Structural Materials Research Laboratory, Lewis Institute.

It is obvious that equations of many different types may be used.

The values given in Table XXVIII indicate that the consistency of the concrete has little influence on the rate of change of strength due to fineness of grinding of the cement. There is an exception to this conclusion in the case of the very wet mixtures, in which the benefit of fine grinding is somewhat reduced.

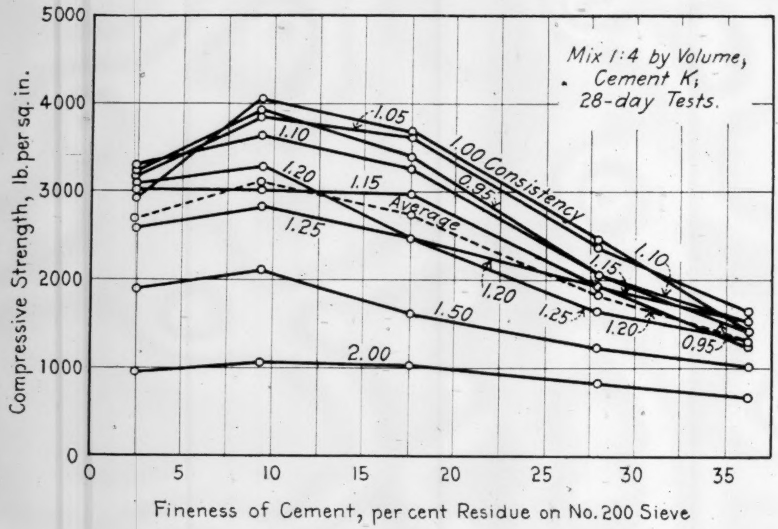

FIG. 21.—Effect of Fineness of Cement on the Strength of Concrete—Series 118.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table XVIII. Aggregate; sand and pebbles from Elgin, Ill., graded 0–¾ in.

Quantity of Cement.—The effect of fineness of cement was studied in a wide range of mixes. Series 20 included two concrete mixtures; Series 31, five mixtures; Series 118, two mixtures; Series 120, six mixtures, ranging from 1:10 to 1:2. The mortar tests included mixtures up to neat cement. The curves in Figs. 12 and 35 show the effect of quantity of cement for typical cements. The cement is expressed in terms of the volume of the finished concrete. The rate of change in strength with cement can be calculated from the slopes of these curves. Rates calculated in this way have been platted from Series 120 in Fig. 36, and from Series 31 in Figs. 13 and 14. For a given plastic condition the strength of concrete increased with the quantity of cement for all finenesses and consistencies. The rate of increase is higher for the lean than for the rich mixes, and is practically independent of the consistency of the concrete. It is higher at early periods than at later ages. The fineness of cement has little or no effect on the rate of increase in strength of concrete due to a given increase in cement content. For ordinary mixtures, increasing the quantity of cement 1 per cent increases the strength about 1 per cent. It will be noted

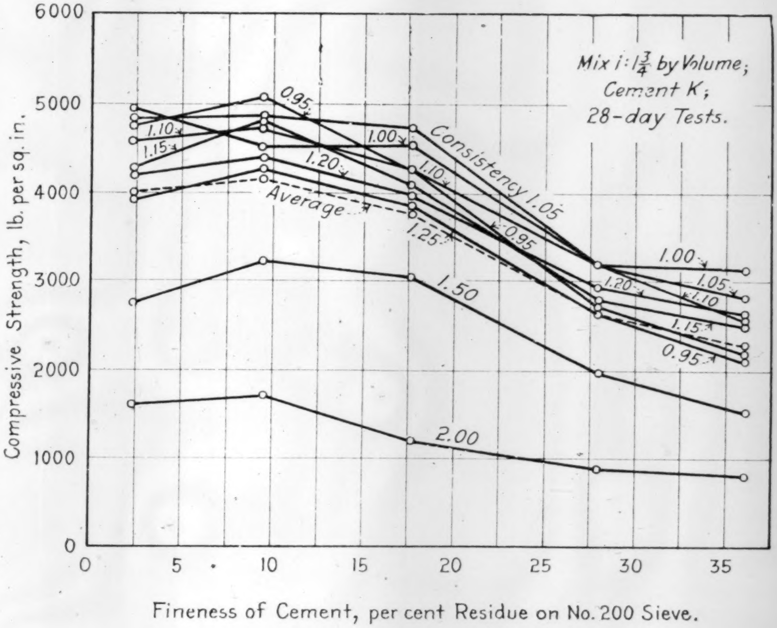

FIG. 22.—Effect of Fineness of Cement on the Strength of Concrete—Series 118.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table XVIII.
Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.

that a unit volume of very wet concrete of a given mix contains considerably less cement than mixes of normal consistency.

In the foregoing discussion it should be understood that 1 per cent increase in cement refers to the actual change in cement content. If we assume that 1:5 mix contains 20 per cent of cement (by volume of finished concrete), then an increase of 1 per cent would give a cement content of 20.2 per cent (not 21 per cent as frequently stated).

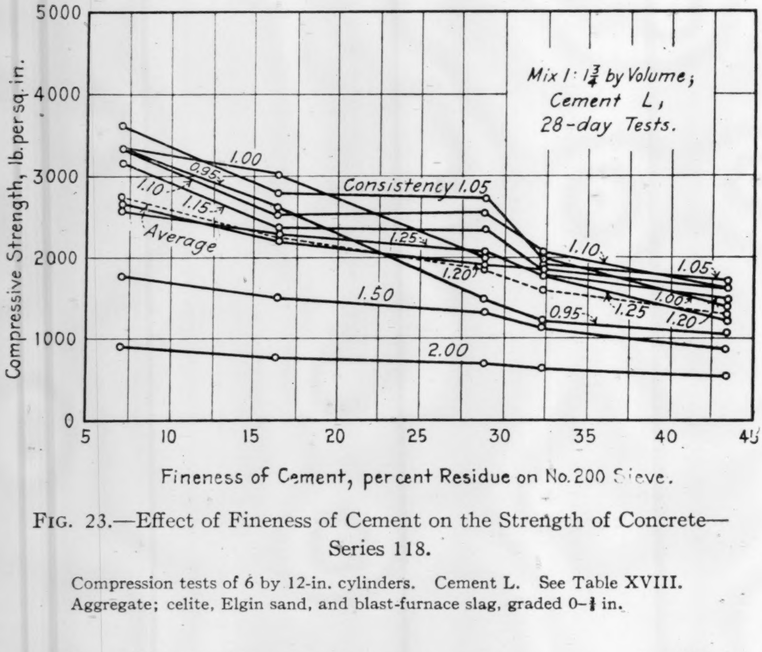

FIG. 23.—Effect of Fineness of Cement on the Strength of Concrete—Series 118.

Compression tests of 6 by 12-in. cylinders. Cement L. See Table XVIII. Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.

Size and Grading of Aggregate.—Aggregates of different sizes and grading were used in Series 60 and 120. The effect of fineness of cement with aggregates of different gradings is shown in Figs. 19 and 34. The tests show an increase in strength with the fineness modulus of the aggregate similar to that observed in other tests made in this Laboratory. The reason for this relation is found in the fact that the water content for a given plastic condition of the concrete is dependent on the size and grading of the aggregate as measured by the fineness modulus.

The finer aggregate shows a somewhat greater increase in strength with fineness of cement than the coarser gradings. (See Table XXIX.)

Age of Concrete.—Tests were made in Series 20, 31, 60 and 120 at ages varying from 7 days to 1 year. The results of these tests are given in Tables X, XIV, XXIV, and XXVI. Fig. 15 gives typical age-strength curves. It will be noted that the strength of the concrete increases with age for both of the mixtures

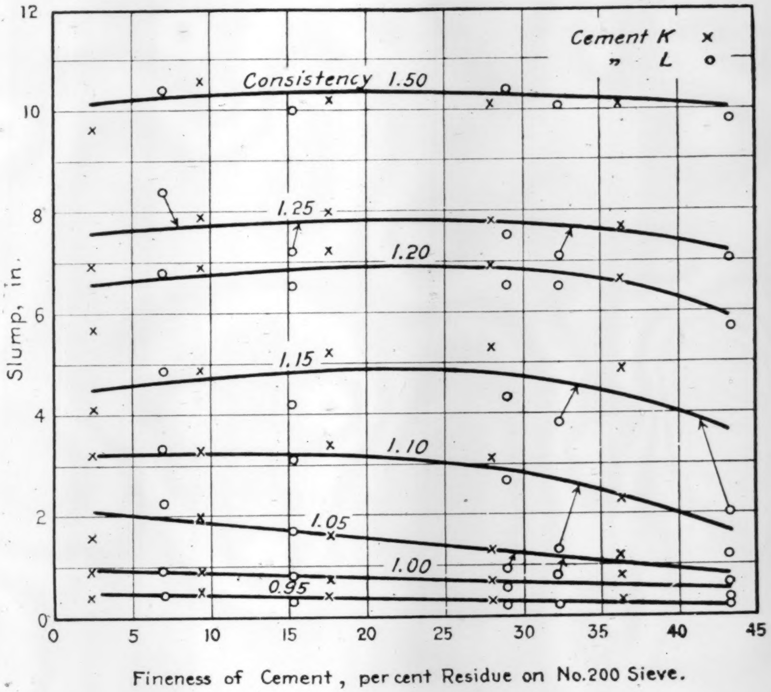

FIG. 24.—Effect of Fineness of Cement on the Workability of Concrete—Series 118.

Tests on 6 by 12-in. cylinders. Cements K and L. See Table XXI.
Mix 1:1¾ by volume.
Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.
Apparatus for "slump" tests shown in Fig. 1.
Each value is the average of 5 tests made on different days.

TABLE XXIII.—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Mix by volume.
Aggregate, sand and pebbles from Elgin, Ill., graded 0-1½ in. Age at test, 28 days.
Specimens stored in damp sand; tested damp. Each value is the average of 5 tests made on different days.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.

Mix by by Volume.	Compressive Strength for Different Relative Consistencies, lb. per sq. in.													
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
	CEMENT K-1—(2.4).[1]							CEMENT L-1—(7.1).[1]						
1:10......	1320	1380	1220	930	640	390	980	910	820	870	610	480	310	670
1:7.......	2690	2540	2150	1520	900	630	1740	1770	1640	1310	950	650	450	1130
1:5.......	3830	3200	2900	2200	1380	720	2370	2970	2780	2060	1380	910	690	1800
1:4.......	3670	3690	3100	2630	1670	920	2610	2910	3850	2290	1380	1090	650	2030
1:3.......	4140	4170	3700	3000	2220	1020	3040	4750	3590	3380	2330	1360	740	2690
1:2.......	4600	4440	4260	3800	2880	1610	3600	5140	5020	4060	3560	2510	1080	3560
Average...	3380	3240	2890	2350	1620	880	2380	3080	2950	2330	1700	1170	650	1980
	CEMENT K-2—(9.4).[1]							CEMENT L-2—(16.3).[1]						
1:10......	1410	1420	1190	1130	800	560	1080	540	530	560	510	360	230	460
1:7.......	2090	2450	2370	1630	1050	750	1720	930	1080	1040	730	570	380	790
1:5.......	3550	3920	3260	2440	1490	860	2590	1420	1710	1580	1110	850	550	1200
1:4.......	3790	4340	3620	2820	2030	1060	2940	1800	2130	1740	1330	940	630	1430
1:3.......	4770	5370	4680	3990	2530	1140	3750	2330	2450	2030	1950	1220	630	1770
1:2.......	4270	5270	5300	4360	3540	1540	4050	2290	3780	3040	2660	1880	800	2410
Average...	3310	3800	3400	2730	1910	980	2690	1550	1950	1660	1380	970	540	1350
	CEMENT K-3—(17.7).[1]							CEMENT L-3—(28.9).[1]						
1:10......	1140	930	1060	880	620	440	840	470	740	460	440	350	200	450
1:7.......	1760	1680	1630	1210	930	640	1310	980	930	820	710	500	350	720
1:5.......	2330	2990	2700	2070	1280	920	2050	1280	1540	1440	1010	610	480	1060
1:4.......	3350	3550	3290	2550	1510	890	2520	1570	1900	1580	1240	740	530	1260
1:3.......	4050	4190	3380	2970	2060	1150	2970	1740	2050	1750	1520	990	500	1420
1:2.......	4030	4900	4430	3530	2640	1330	3480	1670	3060	2580	2080	1300	800	1920
Average...	2780	3040	2750	2200	1510	900	2200	1280	1700	1440	1170	750	480	1140
	CEMENT K-4—(27.9).[1]							CEMENT L-4—(32.3).[1]						
1:10......	750	620	710	580	500	330	580	340	390	340	350	320	250	330
1:7.......	1170	1250	1190	970	710	520	970	460	610	490	560	550	280	490
1:5.......	1850	2090	2000	1490	1050	630	1520	1000	1040	1080	800	610	400	820
1:4.......	2440	2590	2450	1780	1140	720	1850	740	1750	1390	1200	810	450	1060
1:3.......	3240	3420	3050	2530	1350	860	2410	990	2030	1910	1350	830	530	1270
1:2.......	3000	3800	3900	3260	1690	950	2770	1660	2730	2270	1730	1300	930	1770
Average...	2080	2300	2220	1770	1070	670	1680	860	1420	1250	1000	740	470	960
	CEMENT K-5—(36.2).[1]							CEMENT L-5—(43.3).[1]						
1:10......	530	490	530	440	440	300	460	390	290	290	340	230	150	280
1:7.......	910	860	870	940	550	470	770	440	360	470	400	370	200	370
1:5.......	1480	1480	1340	1020	850	730	1150	840	920	730	760	500	400	690
1:4.......	1390	1950	1830	1350	980	600	1350	900	1010	1030	920	750	560	860
1:3.......	2330	2730	2340	1730	1060	730	1820	1120	1460	1480	1100	830	730	1120
1:2.......	2860	3580	3160	2520	1590	880	2430	920	1840	1640	1400	730	730	1210
Average...	1580	1850	1680	1330	910	620	1330	770	980	940	820	570	460	760

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[1] Fineness of cement, residue on No. 200 sieve.

used and for all finenesses of cement.[1] Similar curves may be platted from the data in Series 20 and 120. Curves for concrete of different ages are shown in many of the diagrams.

TABLE XXIV.—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

(A STUDY OF CONSISTENCY.)

Compression tests of 6 by 12-in. cylinders.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.
Aggregate sand and pebbles from Elgin, Ill., graded 0–1½ in.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests made on different days.
Tests at 1 year will be made at a later date.

CEMENT K.

1:4 Mix.

Cement.		Compressive Strength for Different Relative Consistencies, lb. per sq. in.						
Ref. No.	Fineness Residue on No. 200 Sieve.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
7-DAY TESTS.								
K-1.....	2.4	2410	2370	2080	1560	1010	450	1650
K-2.....	9.4	2840	2650	2320	1890	940	470	1840
K-3.....	17.7	2170	2000	1640	1220	690	420	1360
K-4.....	27.9	1490	1350	1180	810	480	300	940
K-5.....	36.2	1050	1010	890	610	360	260	700
Average..............		1990	1880	1620	1220	700	380	1300
28-DAY TESTS.[1]								
K-1.....	2.4	3670	3690	3100	2630	1670	920	2610
K-2.....	9.4	3790	4340	3620	2820	2030	1060	2940
K-3.....	17.7	3350	3550	3290	2550	1510	890	2520
K-4.....	27.9	2440	2590	2450	1780	1140	720	1850
K-5.....	36.2	1390	1950	1830	1350	980	600	1350
Average..............		2930	3220	2860	2230	1470	840	2250
3-MONTH TESTS.								
K-1.....	2.4	4180	4060	3100	2790	2090	1170	2900
K-2.....	9.4	4190	4820	4580	3640	2420	1290	3490
K-3.....	17.7	4020	4480	3820	3430	1930	1240	3170
K-4.....	27.9	3330	3460	2980	2190	1300	920	2360
K-5.....	36.2	2650	2930	2450	1970	1230	890	2020
Average..............		3670	3950	3410	2800	1790	1100	2790

[1] The 28-day tests in this table are the same as the 1:4 tests in Table XXIII.

The effect of age on the change of strength of concrete with the fineness of cement is shown in Figs. 7 and 11, and in Tables

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[1] See D. A. Abrams, "Effect of Age on the Strength of Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 317 (1918).

TABLE XXV.—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 120.

Strength tests given in Tables XXIII and XXIV.

Water reported on basis of true volume of cement, that is, the differences in unit weights of the cements are taken in account.

Mix by Volume.	Ratio of Water to Volume of Cement for Different Relative Consistencies.											
	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
	CEMENT K-1—(2.4).[1]						CEMENT L-1—(7.1).[1]					
1:10	1.00	1.11	1.23	1.40	1.67	2.23	1.07	1.19	1.31	1.49	1.78	2.38
1:7	0.79	0.88	0.96	1.10	1.32	1.76	0.83	0.93	1.02	1.16	1.39	1.85
1:5	0.64	0.71	0.78	0.89	1.06	1.42	0.67	0.75	0.82	0.93	1.12	1.49
1:4	0.57	0.63	0.69	0.79	0.94	1.26	0.59	0.66	0.73	0.83	0.99	1.32
1:3	0.49	0.55	0.60	0.68	0.82	1.09	0.52	0.57	0.63	0.72	0.86	1.15
1:2	0.42	0.47	0.51	0.58	0.70	0.94	0.44	0.49	0.54	0.61	0.74	0.98
	CEMENT K-2—(9.4).[1]						CEMENT L-2—(16.3).[1]					
1:10	1.09	1.22	1.34	1.51	1.83	2.43	1.18	1.30	1.43	1.63	1.95	2.60
1:7	0.86	0.95	1.05	1.19	1.42	1.90	0.92	1.02	1.12	1.27	1.53	2.04
1:5	0.69	0.76	0.84	0.96	1.15	1.53	0.74	0.82	0.90	1.02	1.22	1.63
1:4	0.61	0.68	0.75	0.84	1.01	1.36	0.65	0.72	0.79	0.90	1.08	1.45
1:3	0.53	0.59	0.65	0.73	0.88	1.18	0.56	0.62	0.69	0.78	0.94	1.25
1:2	0.45	0.50	0.55	0.62	0.75	0.99	0.48	0.53	0.58	0.66	0.80	1.06
	CEMENT K-3—(17.7).[1]						CEMENT L-3—(28.9).[1]					
1:10	1.18	1.30	1.43	1.63	1.95	2.60	1.27	1.40	1.54	1.75	2.11	2.80
1:7	0.92	1.02	1.12	1.28	1.53	2.04	0.98	1.09	1.20	1.36	1.63	2.18
1:5	0.74	0.82	0.90	1.02	1.22	1.64	0.78	0.87	0.96	1.09	1.31	1.75
1:4	0.65	0.72	0.80	0.90	1.09	1.45	0.69	0.77	0.85	0.96	1.15	1.54
1:3	0.56	0.63	0.69	0.78	0.94	1.26	0.60	0.66	0.73	0.83	0.99	1.33
1:2	0.48	0.53	0.58	0.66	0.80	1.06	0.50	0.56	0.61	0.70	0.84	1.12
	CEMENT K-4—(27.9).[1]						CEMENT L-4—(32.3).[1]					
1:10	1.28	1.42	1.56	1.78	2.14	2.85	1.31	1.46	1.61	1.82	2.20	2.92
1:7	1.00	1.11	1.22	1.39	1.67	2.23	1.05	1.14	1.25	1.43	1.70	2.28
1:5	0.80	0.89	0.98	1.11	1.34	1.78	0.82	0.91	1.00	1.13	1.36	1.82
1:4	0.71	0.79	0.86	0.98	1.18	1.58	0.72	0.80	0.88	1.00	1.20	1.60
1:3	0.61	0.68	0.75	0.85	1.02	1.36	0.62	0.69	0.76	0.86	1.04	1.38
1:2	0.52	0.58	0.63	0.72	0.86	1.15	0.52	0.58	0.64	0.73	0.87	1.16
	CEMENT K-5—(36.2).[1]						CEMENT L-5—(43.3).[1]					
1:10	1.34	1.49	1.64	1.86	2.23	2.98	1.34	1.49	1.64	1.87	2.24	2.99
1:7	1.04	1.15	1.26	1.44	1.72	2.30	1.04	1.15	1.27	1.44	1.74	2.31
1:5	0.83	0.92	1.02	1.15	1.38	1.83	0.82	0.92	1.01	1.14	1.37	1.83
1:4	0.73	0.82	0.90	1.02	1.23	1.63	0.73	0.80	0.88	1.01	1.20	1.61
1:3	0.64	0.71	0.78	0.88	1.06	1.41	0.62	0.69	0.76	0.86	1.04	1.38
1:2	0.54	0.59	0.65	0.74	0.89	1.19	0.52	0.58	0.63	0.72	0.86	1.15

[1] Fineness of cement, residue on No. 200 sieve.

XX, XXVIII and XXIX. It is seen that the rate of change of strength decreases rapidly with the age of the concrete. A study of all of the data shows that for usual mixtures tested at 28 days the increase in strength of the concrete is about 2 per cent for each 1 per cent reduction in residue on the No. 200

TABLE XXVI.—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

(A STUDY OF SIZE OF AGGREGATE.)

Compression tests of 6 by 12-in. cylinders.
Consistency 1.10.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.
Aggregate, sand and pebbles from Elgin, Ill.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests.
Tests at 1 year will be made at a later date.

CEMENT K.

1:4 Mix.

Ref. No.	Cement. Fineness Residue on No. 200 Sieve.	Compressive Strength for Aggregates of Different Sizes, lb. per sq. in. 0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–$\frac{3}{8}$ in.	0–$\frac{3}{4}$ in.	0–$1\frac{1}{2}$ in.	Average.
7-DAY TESTS.									
K-1	2.4	410	590	730	980	1260	1940	2080	1140
K-2	9.4	390	580	790	1020	1500	1920	2320	1220
K-3	17.7	320	410	560	680	1170	1700	1640	930
K-4	27.9	210	310	390	440	700	1040	1180	610
K-5	36.2	140	200	250	380	470	780	890	450
Average		290	420	550	700	1020	1480	1620	870
28-DAY TESTS.									
K-1	2.4	680	940	1200	1340	2350	2630	3100	1750
K-2	9.4	630	960	1260	1650	2580	2860	3620	1940
K-3	17.7	470	750	1010	1260	1760	2830	3290	1620
K-4	27.9	360	560	670	880	1290	1790	2450	1140
K-5	36.2	220	440	500	680	1080	1420	1830	880
Average		470	730	930	1160	1810	2310	2860	1470
3-MONTH TESTS.									
K-1	2.4	940	1500	1890	2050	2760	3450	3100	2240
K-2	9.4	940	1390	1860	2280	3590	3970	4580	2660
K-3	17.7	630	1150	1430	1930	2860	3990	3920	2270
K-4	27.9	570	890	1150	1410	2160	2830	2980	1710
K-5	36.2	410	650	870	980	1740	2280	2450	1340
Average		700	1120	1440	1730	2620	3300	3410	2040

TABLE XXVII.—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 120.

Strength tests given in Table XXVI.

Water reported on bases of true volume of cement, that is, the differences in unit weights of the cements are taken in account.

Relative consistency 1.10.

Mix 1:4 by volume.

Cement.		Ratio of Water to Volume of Cement for Aggregates of Different Size.						
Ref. No.	Fineness Residue on No. 200 Sieve.	0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–⅜ in.	0–¾ in.	0–1½ in.
K-1	2.4	1.18	1.06	1.01	0.94	0.83	0.75	0.69
K-2	9.4	1.28	1.15	1.09	1.02	0.90	0.80	0.75
K-3	17.7	1.38	1.23	1.17	1.09	0.96	0.86	0.80
K-4	27.9	1.50	1.34	1.28	1.19	1.04	0.93	0.86
K-5	36.2	1.56	1.39	1.32	1.23	1.09	0.97	0.90

TABLE XXVIII.—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 120.

(EFFECT OF CONSISTENCY.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Tables XXIII and XXIV.)

Aggregate, sand and pebbles from Elgin, Ill.

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentages shown.

Mix by Volume.	Age at Test.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per cent of Strength for 20 per cent Residue.						
		0.90[a]	1.00	1.10	1.25	1.50	2.00	Average.
CEMENT K; 0–1½ IN. AGGREGATE.								
1:10	28 days	3.3	3.0	2.4	3.8	1.9	2.2	2.8
1:7	......	2.8	3.1	3.0	2.2	2.4	1.3	2.5
1:5	......	2.5	2.9	2.8	2.9	2.0	1.3	2.4
1:4	......	3.0	2.6	2.4	2.6	2.7	2.1	2.6
1:3	......	2.2	2.1	2.1	2.5	3.0	1.8	2.3
1:2	......	1.8	1.4	1.7	1.8	3.0	2.2	2.0
Average		2.6	2.5	2.4	2.6	2.5	1.8	2.4
CEMENT L; 0–1½ IN. AGGREGATE.								
1:10	28 days	2.0	2.9	2.1	1.5	1.4	1.0	1.8
1:7	......	2.2	3.1	2.5	2.0	1.2	2.2	2.2
1:5	......	1.8	2.0	2.3	1.3	1.3	1.0	1.6
1:4	......	2.4	1.9	1.7	1.1	1.4	0.8	1.5
1:3	......	3.0	1.5	1.2	1.8	1.3	0.8	1.6
1:2	......	2.2	2.0	1.7	2.0	2.4	0.5	1.8
Average		2.3	2.2	1.9	1.6	1.5	1.0	1.8
CEMENT K: 0–1½ IN. AGGREGATE.								
1:4	7 days	3.1	3.2	3.1	3.6	3.2	2.0	3.0
	28 days	3.0	2.6	2.4	2.6	2.7	2.1	2.6
	3 mo.	1.6	1.9	2.2	2.1	2.2	1.7	1.9
Average		2.6	2.6	2.6	2.8	2.7	1.9	2.5

[a] Relative consistency of concrete.

TABLE XXIX.—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 120.

(EFFECT OF SIZE OF AGGREGATE.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Table XXVI.)

Aggregate, sand and pebbles from Elgin, Ill.

Cement K, relative consistency 1.10.

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentages shown.

Mix by Volume.	Age at Test.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per cent of Strength for 20 per cent Residue.							
		0–No. 28[a]	0–No.14	0–No. 8	0–No. 4	0–⅜ in.	0–¾ in.	0–1½ in.	Average.
1:4.......	7 days	4.0	2.2	3.2	3.2	3.4	2.6	3.1	3.1
	28 days	3.3	2.9	2.9	2.8	2.6	2.5	2.4	2.8
	3 mos.	2.6	2.5	2.5	2.8	2.3	2.0	2.2	2.4
Average.............		3.3	2.5	2.9	2.9	2.8	2.4	2.6	2.8

[a] Size of aggregate.

TABLE XXX.—SLUMP TESTS FOR CONSISTENCY OF CONCRETE—SERIES 120.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady, upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Aggregate, sand and pebbles from Elgin, Ill.

Relative consistency 1.10.

Each value is the average of 5 tests made on different days.

Ref. No.	Fineness Residue on No. 200 Sieve.	Slump for Different Sizes of Aggregate, in.							
		0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–⅜ in.	0–¾ in.	0–1½ in.	Average.
K-1.......	2.4	0.4	0.5	1.0	2.1	4.3	4.1	2.6	2.1
K-2.......	9.4	0.2	0.3	0.4	3.1	5.3	5.4	5.0	2.8
K-3.......	17.7	0.1	0.2	0.6	0.4	3.0	4.5	5.0	2.0
K-4.......	27.9	0.1	0.2	0.7	0.3	0.5	2.3	1.2	0.8
K-5.......	36.2	0.3	1.2	1.0	0.3	0.4	1.7	1.8	1.0
Average..............		0.2	0.5	0.7	1.2	2.7	3.6	3.1	1.7

TABLE XXXI.—SLUMP TESTS FOR CONSISTENCY OF CONCRETE—SERIES 120.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady, upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Aggregate, sand and pebbles from Elgin, Ill., graded 0–1½ in.

Each value for Cement K is the average of 5 tests; for Cement L the average of 3 tests.

Mix by Volume.	Slump for Different Consistencies, in.											
	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
	CEMENT K-1—(2.4).[1]						CEMENT L-1—(7.1).[1]					
1:10	2.9	1.4	3.0	5.0	6.8	7.5	7.4	2.6	4.1	7.4	7.6	7.4
1:7	0.2	0.4	0.4	4.7	8.1	8.6	0.1	0.1	3.0	4.2	8.7	8.0
1:5	2.8	8.5	3.8	6.7	8.8	....	2.4	0.7	2.0	5.8	8.1	....
1:4	0.3	0.9	2.6	8.3	9.1	....	0.3	5.8	4.4	7.7	8.8	....
1:3	0.6	2.8	5.9	8.3	9.3	....	0.6	3.6	7.6	8.9	9.3	....
1:2	0.2	0.8	3.8	7.9	8.4	....	0.4	1.6	7.0	9.3	10.3	....
Average	1.2	2.5	3.2	6.8	8.4	....	1.9	2.4	4.7	7.2	8.8	7.7
	CEMENT K-2—(9.4).[1]						CEMENT L-2—(16.3).[1]					
1:10	3.0	5.3	4.4	1.9	6.8	7.6	7.6	5.8	5.4	0.1	5.9	6.8
1:7	1.5	0.1	0.3	5.6	7.0	7.6	0.2	0.1	0.3	1.4	2.8	8.0
1:5	0.2	0.6	1.9	4.3	8.8	....	0.1	0.4	2.2	2.9	3.9	5.8
1:4	0.2	0.6	5.0	6.0	8.2	....	0.2	0.4	2.3	5.7	6.1	8.7
1:3	0.3	0.9	4.2	7.4	8.3	....	0.2	2.0	6.7	7.7	8.6	9.0
1:2	0.2	0.8	2.9	8.0	8.6	....	0.1	1.1	3.4	8.2	9.1	....
Average	0.9	1.4	3.1	5.5	8.0	....	1.4	1.6	3.4	4.3	6.1	7.7
	CEMENT K-3—(17.7).[1]						CEMENT L-3—(28.9).[1]					
1:10	6.9	3.1	4.3	4.2	6.6	6.3	7.1	4.6	4.4	4.5	7.0	6.2
1:7	1.4	0.2	0.4	0.4	3.1	8.0	2.3	0.2	0.4	2.7	5.2	8.1
1:5	0.1	0.4	1.3	4.1	6.9	7.3	0.1	0.3	0.9	3.9	3.1	6.3
1:4	0.2	2.0	5.0	6.0	7.6	....	0.1	0.4	1.5	6.3	4.5	7.1
1:3	0.3	2.0	5.5	7.8	9.1	....	0.2	0.6	5.0	6.9	7.9	....
1:2	0.2	1.1	4.6	8.4	8.3	....	0.1	2.9	4.3	8.7	9.0	....
Average	1.5	1.5	3.5	5.2	6.9	....	1.6	1.5	2.7	5.5	6.1	6.9
	CEMENT K-4—(27.9).[1]						CEMENT L-4—(32.3).[1]					
1:10	7.5	6.2	5.1	5.7	6.1	7.0	7.5	7.2	7.4	4.8	6.6	5.9
1:7	3.0	0.3	0.1	0.2	5.0	7.4	2.4	2.0	2.6	3.0	2.0	6.7
1:5	0.1	0.2	0.6	1.5	4.6	....	0.1	0.1	0.4	1.2	4.8	7.6
1:4	0.1	0.4	1.2	4.2	5.4	4.2	0.1	0.5	2.8	4.2	4.1	....
1:3	0.3	1.5	4.6	7.9	6.7	....	0.1	1.3	5.3	7.2	7.1	....
1:2	0.3	0.6	5.2	8.3	8.3	....	0.1	0.6	5.7	8.2	3.4	....
Average	1.9	1.5	2.8	4.6	6.0	....	1.7	2.0	4.0	4.8	4.7	6.7
	CEMENT K-5—(36.2).[1]						CEMENT L-5—(43.3).[1]					
1:10	6.8	7.4	6.8	4.3	4.5	6.4	7.7	7.7	6.7	4.0	....	....
1:7	3.6	1.5	0.2	0.3	1.6	5.1	6.7	4.5	2.7	5.3	....	....
1:5	2.4	0.2	1.8	1.1	3.3	4.8	1.7	0.1	0.2	1.3	....	....
1:4	0.1	0.3	1.8	3.4	3.9	....	2.5	0.1	1.3	4.1	....	....
1:3	0.2	0.6	4.4	7.2	5.9	....	0.1	0.3	1.2	6.7	....	....
1:2	0.1	0.8	5.3	8.3	8.3	....	0.3	0.8	6.4	8.6	9.4	....
Average	2.2	1.8	3.4	4.1	4.6	....	3.2	2.2	3.1	5.0	....	....

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[1] Fineness of cement, residue on No. 200 sieve.

TABLE XXXII.—EFFECT OF FINENESS OF CEMENT ON YIELD AND DENSITY OF CONCRETE.—SERIES 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill., graded 0-1½ in.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Yield for Different Consistencies.							Density for Different Consistencies.						
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
CEMENT K-1—(2.4).[1]														
1:10..	1.001	1.000	0.993	0.995	1.002	1.052	1.007	0.814	0.815	0.821	0.820	0.813	0.774	0.809
1:7...	0.995	0.993	1.007	1.024	1.039	1.079	1.023	0.840	0.842	0.831	0.815	0.804	0.773	0.817
1:5...	1.018	1.038	1.045	1.070	1.081	1.141	1.065	0.848	0.832	0.826	0.806	0.797	0.756	0.811
1:4...	1.060	1.076	1.090	1.119	1.146	1.195	1.114	0.837	0.825	0.814	0.794	0.775	0.743	0.798
1:3...	1.140	1.150	1.164	1.187	1.218	1.285	1.191	0.814	0.807	0.797	0.783	0.763	0.722	0.781
1:2...	1.294	1.289	1.309	1.335	1.377	1.467	1.345	0.779	0.783	0.770	0.756	0.733	0.688	0.751
Avg...	1.085	1.091	1.101	1.121	1.144	1.203	1.124	0.822	0.817	0.810	0.782	0.781	0.743	0.794
CEMENT K-2—(9.4).[1]														
1:10..	1.015	1.005	0.991	0.987	1.008	1.035	1.007	0.802	0.810	0.822	0.825	0.808	0.788	0.809
1:7...	1.020	1.005	0.998	1.007	1.037	1.076	1.024	0.818	0.831	0.837	0.829	0.805	0.776	0.816
1:5...	1.028	1.023	1.036	1.052	1.079	1.127	1.057	0.840	0.845	0.833	0.820	0.800	0.767	0.817
1:4...	1.068	1.061	1.075	1.088	1.120	1.175	1.098	0.830	0.836	0.825	0.816	0.792	0.755	0.809
1:3...	1.160	1.130	1.148	1.168	1.205	1.260	1.178	0.800	0.822	0.808	0.795	0.770	0.737	0.789
1:2...	1.314	1.265	1.291	1.320	1.358	1.447	1.332	0.767	0.797	0.780	0.764	0.743	0.697	0.758
Avg...	1.101	1.082	1.090	1.104	1.134	1.187	1.116	0.810	0.824	0.818	0.808	0.786	0.753	0.800
CEMENT K-3—(17.7).[1]														
1:10..	1.028	1.012	1.005	0.987	1.005	1.042	1.013	0.793	0.804	0.810	0.826	0.810	0.782	0.804
1:7...	1.027	1.011	1.011	1.014	1.030	1.061	1.026	0.813	0.826	0.826	0.823	0.810	0.787	0.814
1:5...	1.036	1.027	1.042	1.050	1.070	1.111	1.056	0.833	0.841	0.829	0.823	0.807	0.777	0.818
1:4...	1.073	1.060	1.073	1.090	1.125	1.173	1.099	0.827	0.837	0.827	0.814	0.788	0.756	0.808
1:3...	1.136	1.138	1.147	1.168	1.200	1.254	1.174	0.817	0.816	0.810	0.796	0.772	0.740	0.792
1:2...	1.305	1.275	1.282	1.308	1.338	1.425	1.322	0.772	0.790	0.785	0.771	0.753	0.707	0.763
Avg...	1.102	1.087	1.093	1.103	1.128	1.178	1.115	0.809	0.819	0.814	0.809	0.790	0.758	0.800
CEMENT K-4—(27.9).[1]														
1:10..	1.029	1.028	1.005	1.012	1.012	1.041	1.021	0.792	0.793	0.811	0.805	0.805	0.783	0.798
1:7...	1.032	1.020	1.011	1.006	1.036	1.076	1.030	0.808	0.818	0.826	0.830	0.806	0.776	0.811
1:5...	1.057	1.035	1.042	1.051	1.076	1.119	1.063	0.817	0.834	0.828	0.821	0.802	0.771	0.812
1:4...	1.088	1.072	1.081	1.091	1.127	1.173	1.105	0.817	0.826	0.820	0.812	0.787	0.756	0.803
1:3...	1.143	1.135	1.145	1.159	1.203	1.255	1.173	0.812	0.818	0.811	0.801	0.771	0.740	0.792
1:2...	1.321	1.280	1.291	1.308	1.355	1.431	1.331	0.763	0.789	0.780	0.772	0.744	0.704	0.759
Avg...	1.112	1.095	1.098	1.104	1.135	1.182	1.120	0.802	0.813	0.813	0.807	0.786	0.755	0.796
CEMENT K-5—(36.2).[1]														
1:10..	1.027	1.025	1.018	1.012	1.020	1.054	1.026	0.794	0.795	0.801	0.805	0.800	0.772	0.794
1:7...	1.040	1.031	1.018	1.021	1.035	1.074	1.036	0.803	0.810	0.822	0.819	0.807	0.777	0.806
1:5...	1.056	1.041	1.054	1.058	1.082	1.116	1.068	0.817	0.829	0.818	0.816	0.797	0.774	0.808
1:4...	1.100	1.080	1.088	1.100	1.125	1.171	1.111	0.806	0.821	0.816	0.806	0.788	0.757	0.799
1:3...	1.165	1.135	1.143	1.164	1.195	1.246	1.175	0.796	0.818	0.811	0.797	0.777	0.745	0.791
1:2...	1.310	1.270	1.300	1.315	1.351	1.429	1.329	0.770	0.793	0.775	0.766	0.745	0.705	0.759
Avg...	1.116	1.197	1.104	1.112	1.135	1.182	1.124	0.798	0.811	0.807	0.802	0.786	0.755	0.793

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[1] Fineness of cement, residue on No. 200 sieve.

Table XXXIII.—Effect of Fineness of Cement on Yield and Density of Concrete—Series 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill., graded 0–1½ in.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Yield for Different Consistencies.							Density for Different Consistencies.						
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
Cement L-1—Fineness 7.1.														
1:10..	1.008	1.012	1.998	1.000	1.005	1.042	1.011	0.809	0.805	0.816	0.815	0.810	0.782	0.806
1:7...	1.005	0.998	1.004	1.021	1.043	1.070	1.023	0.830	0.837	0.831	0.818	0.800	0.781	0.816
1:5...	1.022	1.029	1.036	1.052	1.071	1.120	1.055	0.844	0.839	0.834	0.820	0.806	0.771	0.819
1:4...	1.073	1.073	1.073	1.101	1.134	1.175	1.105	0.826	0.826	0.826	0.806	0.781	0.755	0.803
1:3...	1.112	1.137	1.153	1.168	1.198	1.260	1.171	0.833	0.816	0.805	0.795	0.775	0.737	0.793
1:2...	1.270	1.272	1.302	1.320	1.359	1.434	1.326	0.793	0.791	0.773	0.763	0.742	0.703	0.761
Avg...	1.082	1.087	1.094	1.110	1.135	1.184	1.115	0.822	0.819	0.814	0.803	0.786	0.755	0.800
Cement L-2—Fineness 16.3.														
1:10..	1.036	1.027	1.032	1.005	1.041	1.050	1.032	0.787	0.794	0.790	0.811	0.782	0.777	0.790
1:7...	1.049	1.019	1.012	1.014	1.036	1.082	1.035	0.796	0.820	0.824	0.823	0.806	0.771	0.807
1:5...	1.056	1.035	1.050	1.051	1.076	1.119	1.064	0.818	0.834	0.822	0.821	0.803	0.772	0.812
1:4...	1.088	1.073	1.080	1.091	1.125	1.180	1.106	0.816	0.826	0.821	0.813	0.788	0.752	0.803
1:3...	1.175	1.135	1.150	1.159	1.203	1.248	1.183	0.790	0.817	0.807	0.801	0.771	0.744	0.788
1:2...	1.350	1.280	1.290	1.316	1.355	1.440	1.338	0.747	0.787	0.782	0.766	0.744	0.700	0.741
Avg...	1.112	1.095	1.102	1.106	1.139	1.186	1.126	0.792	0.813	0.808	0.806	0.782	0.753	0.790
Cement L-3—Fineness 28.9.														
1:10..	1.050	1.055	1.024	1.020	1.020	1.069	1.039	0.776	0.772	0.795	0.799	0.799	0.762	0.784
1:7...	1.039	1.039	1.023	1.032	1.057	1.079	1.045	0.804	0.804	0.815	0.808	0.791	0.774	0.799
1:5...	1.070	1.055	1.048	1.058	1.090	1.118	1.073	0.806	0.818	0.823	0.816	0.792	0.772	0.804
1:4...	1.100	1.085	1.085	1.098	1.124	1.171	1.110	0.806	0.818	0.818	0.808	0.789	0.757	0.799
1:3...	1.182	1.150	1.142	1.172	1.195	1.262	1.184	0.785	0.807	0.812	0.791	0.777	0.735	0.784
1:2...	1.377	1.261	1.287	1.302	1.343	1.400	1.328	0.732	0.798	0.783	0.773	0.750	0.720	0.759
Avg...	1.136	1.108	1.102	1.114	1.138	1.183	1.130	0.785	0.803	0.808	0.799	0.783	0.753	0.788
Cement L-4—Fineness 32.3.														
1:10..	1.056	1.062	1.055	1.040	1.040	1.115	1.061	0.773	0.767	0.773	0.783	0.783	0.731	0.768
1:7...	1.061	1.068	1.051	1.046	1.041	1.094	1.060	0.787	0.782	0.794	0.799	0.802	0.763	0.788
1:5...	1.083	1.062	1.061	1.062	1.089	1.123	1.080	0.797	0.812	0.813	0.812	0.793	0.768	0.799
1:4...	1.139	1.085	1.079	1.089	1.123	1.160	1.112	0.779	0.817	0.822	0.815	0.790	0.765	0.798
1:3...	1.195	1.126	1.141	1.152	1.191	1.243	1.175	0.777	0.824	0.813	0.805	0.779	0.746	0.791
1:2...	1.345	1.270	1.285	1.293	1.348	1.402	1.324	0.749	0.794	0.784	0.779	0.748	0.718	0.762
Avg...	1.150	1.112	1.112	1.114	1.139	1.190	1.135	0.777	0.799	0.799	0.799	0.782	0.748	0.784
Cement L-5—Fineness 43.3.														
1:10..	1.048	1.048	1.038	1.039	1.069	1.051	1.049	0.777	0.777	0.785	0.784	0.763	0.775	0.777
1:7...	1.067	1.051	1.064	1.045	1.053	1.162	1.074	0.782	0.795	0.784	0.799	0.792	0.718	0.778
1:5...	1.090	1.075	1.067	1.070	1.093	1.142	1.089	0.792	0.803	0.810	0.807	0.789	0.756	0.793
1:4...	1.138	1.112	1.091	1.100	1.120	1.157	1.119	0.780	0.797	0.813	0.806	0.792	0.767	0.792
1:3...	1.193	1.161	1.155	1.165	1.195	1.230	1.183	0.776	0.798	0.803	0.796	0.776	0.754	0.784
1:2...	1.391	1.289	1.300	1.295	1.340	1.412	1.338	0.724	0.782	0.775	0.778	0.752	0.714	0.754
Avg...	1.154	1.123	1.119	1.119	1.145	1.192	1.142	0.772	0.792	0.795	0.795	0.777	0.747	0.779

TABLE XXXIV.—EFFECT OF FINENESS OF CEMENT ON YIELD AND DENSITY OF CONCRETE—SERIES 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Relative consistency 1.10.
Each value is the average of 20 tests made on 5 days.

Cement Ref. No.	Yield for Different Sizes of Aggregate.								Density for Different Sizes of Aggregate.							
	0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–3/8 in.	0–3/4 in.	0–1½ in.	Average	0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–3/8 in.	0–3/4 in.	0–1½ in.	Average.
K-1	1.210	1.170	1.150	1.151	1.109	1.108	1.090	1.141	0.621	0.653	0.674	0.704	0.754	0.791	0.814	0.716
K-2	1.196	1.150	1.130	1.140	1.099	1.090	1.075	1.126	0.628	0.664	0.686	0.711	0.760	0.804	0.825	0.726
K-3	1.215	1.148	1.129	1.139	1.082	1.089	1.073	1.125	0.618	0.665	0.687	0.712	0.771	0.805	0.827	0.726
K-4	1.245	1.175	1.146	1.148	1.098	1.097	1.081	1.141	0.603	0.649	0.677	0.706	0.761	0.799	0.820	0.716
K-5	1.267	1.180	1.162	1.155	1.103	1.095	1.088	1.150	0.592	0.646	0.666	0.702	0.757	0.800	0.816	0.711
Average	1.227	1.165	1.143	1.147	1.098	1.096	1.081	1.137	0.612	0.655	0.678	0.707	0.760	0.800	0.820	0.719

TABLE XXXV.—ELONGATION AND CONTRACTION OF CONCRETE—SERIES 120.

Based on length measurements of 180 6 by 12-in. cylinders.
Time intervals refer to the preceding *change* in storage condition.
Plus means an increase in length.
A change in length of 0.001 in. in a 6 by 12-in. cylinder is equivalent to 0.0083 per cent.

Cement.		Mix by Volume.	Relative Consistency.	Change in Length of Cylinder, in.								
Ref. No.	Fineness, Residue on No. 200 Sieve.			28 d. in dampSand.	7 d. in Air.	21 d. in Air.	28 d. in Air.	42 d. in Air.	7 d. in Water.	28 d. in Water.	28 d. in Air.	Total Regardless of Sign.
EFFECT OF FINENESS OF CEMENT.												
K 1	2.4	Values for each fineness are average of all mixes and consistencies (36 cylinders).		−0.002	0.000	−0.003	−0.004	−0.006	+0.003	+0.004	−0.002	0.024
K 2	9.4			+0.002	−0.001	−0.004	−0.005	−0.007	+0.003	+0.004	−0.002	0.028
K 3	17.7			+0.001	0.000	−0.003	−0.005	−0.007	+0.004	+0.004	−0.002	0.026
K 4	27.9			+0.003	−0.004	−0.005	−0.006	−0.006	+0.004	+0.003	−0.001	0.032
K 5	36.9			+0.001	−0.004	−0.004	−0.006	−0.007	+0.004	+0.001	−0.001	0.028
		Grand average[1]		+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	
EFFECT OF QUANTITY OF CEMENT.												
Values for each mix are average of all finenesses and consistencies (30 cylinders).		1:10	....	+0.003	−0.003	−0.004	−0.005	−0.007	+0.003	+0.003	−0.002	0.030
		1:7	....	0.000	−0.002	−0.004	−0.005	−0.007	+0.005	+0.004	−0.002	0.029
		1:5	....	0.000	−0.003	−0.004	−0.006	−0.007	+0.003	+0.003	−0.001	0.027
		1:4	....	−0.001	−0.001	−0.004	−0.005	−0.006	+0.004	+0.004	−0.001	0.026
		1:3	....	0.000	−0.001	−0.003	−0.005	−0.006	+0.004	+0.003	−0.002	0.024
		1:2	....	+0.002	−0.002	−0.005	−0.006	−0.007	+0.003	+0.003	−0.001	0.029
			Grand average[1]	+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	
EFFECT OF CONSISTENCY OF CONCRETE.												
Values for each consistency are average of all finenesses and mixes (30 cylinders).		....	0.90	0.000	−0.002	−0.004	−0.005	−0.007	+0.003	+0.004	−0.002	0.027
		....	1.00	0.000	−0.002	−0.005	−0.005	−0.007	+0.004	+0.004	−0.002	0.029
		....	1.10	0.000	−0.001	−0.003	−0.004	−0.006	+0.004	+0.004	−0.002	0.024
		....	1.25	+0.002	−0.002	−0.004	−0.004	−0.006	+0.004	+0.003	−0.001	0.026
		....	1.50	+0.002	−0.002	−0.004	−0.005	−0.006	+0.004	+0.003	−0.001	0.027
		....	2.00	+0.001	−0.001	−0.004	−0.005	−0.007	+0.003	+0.003	−0.001	0.025
			Grand average[1]	+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	......

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[1] Grand average values are based on measurements on all cylinders.

sieve. At 7 days, 3 months and 1 year the corresponding values are about 2.5, 1.7 and 1.4 per cent. These tests do not bear out the common belief that the strength of the concrete depends only on the "flour" content of the cement, but indicates that fine grinding merely hastens the action of the cement.

Air Analyzer Tests.—The size and grading of the particles in two lots of cement was studied by means of the air analyzer, shown in Fig. 3. This apparatus in combination with the usual sieves enables us to determine the "sieve analysis" of cements in the same manner as for aggregates. The separation sizes were determined by microscopical measurements on a large number of the last particles carried over by the air current or passing the

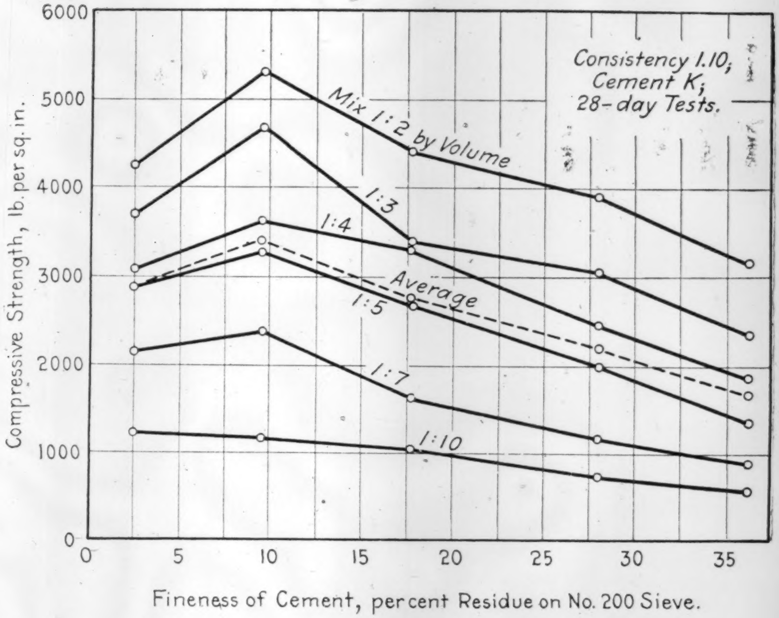

FIG. 25.—Effect of Fineness of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. See Table XXIII.
Cement K. Relative consistency 1.10.
Similar diagrams may be drawn for other consistencies.

sieve. The separations given in Table V for cements K and L show that all the samples give smooth sieve analysis curves of the same type. If these curves are platted it will be seen that the maximum differences in the ordinates (percentages coarser than each size) comes at the No. 200 sieve. We may expect, therefore, that the residue on the No. 200 sieve is a satisfactory measure of fineness of cement.

Further studies of the cements by means of the air analyzer are under way. It is too early to attempt a complete discussion of the function of particles of various sizes in cement.

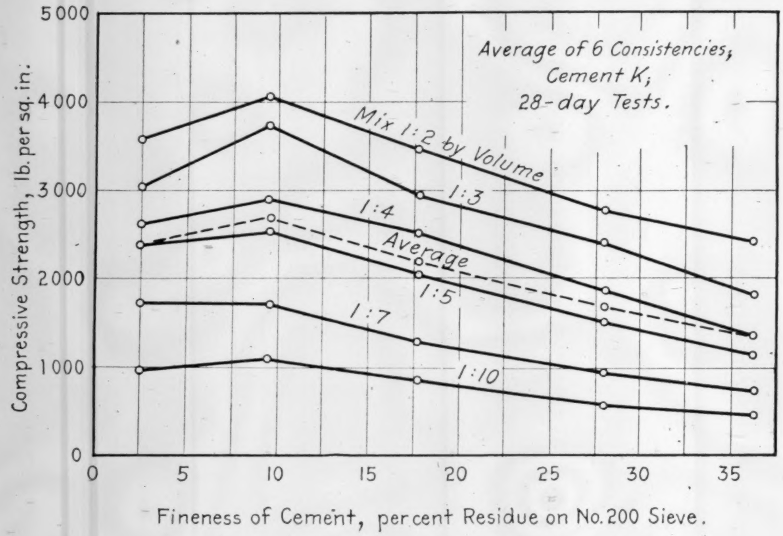

FIG. 26.—Effect of Fineness of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. See Table XXIII.
Cement K. Average of 6 consistencies. Compare Fig. 29.

Mortar Tests.—Mortar tests were made on all the cements used. Little consideration has been given to these tests in the foregoing discussion; however, the tables give the complete results. The compression tests of mortar in general confirm the results of the concrete tests. The briquette tests were erratic

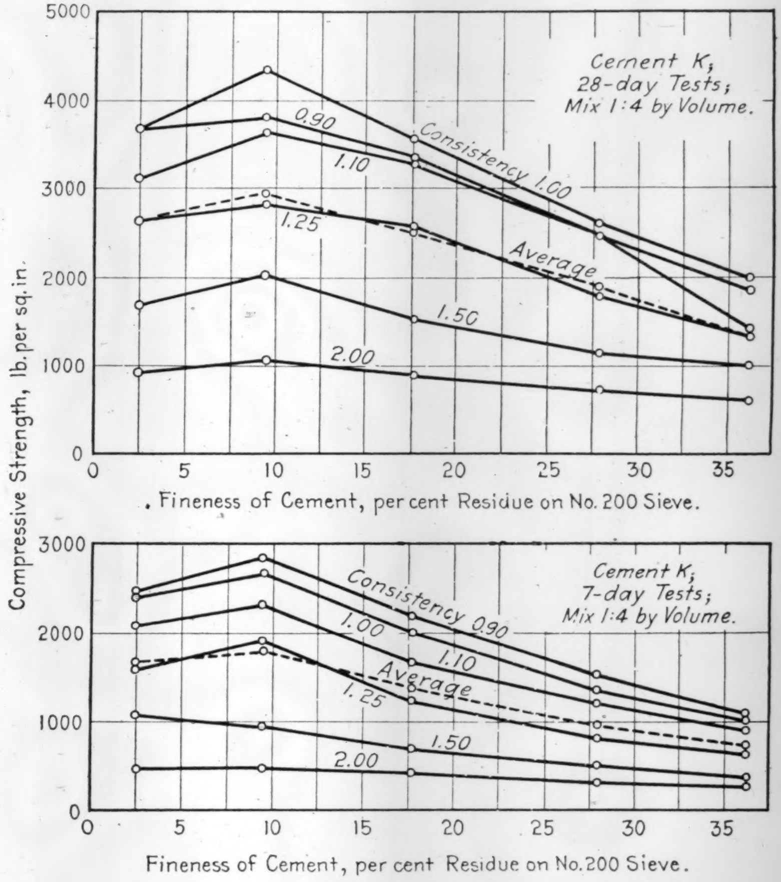

FIG. 27.—Effect of Fineness of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. See Table XXIV.
Cement K. Age at test 7 and 28 days.
The 28-day curve for the 1.10 consistency is the same as the 1:4 mix in Fig. 25.
Similar curves may be drawn for the 3-month tests.

and cannot be interpreted as showing the same relation as found in the concrete investigations. Increase in strength of mortar with the fineness of the cement is shown in Figs. 5, 6 and 10.

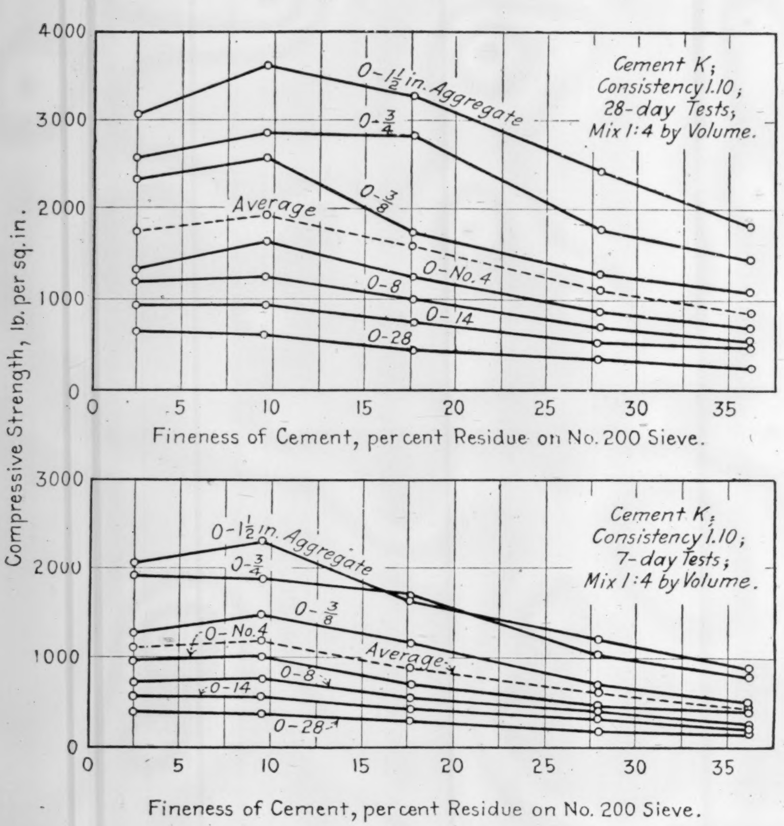

FIG. 28.—Effect of Fineness of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. See Table XXVI.
Cement K. Age at test 7 and 28 days.
The curve for the 0–1½-in. aggregate is the same as for the 1.10 consistency in Fig. 27.

Elongation and Contraction of Concrete.—Tests on the elongation and contraction, due to storage conditions, were made on 180 6 by 12-in. concrete cylinders in Series 120 by means of

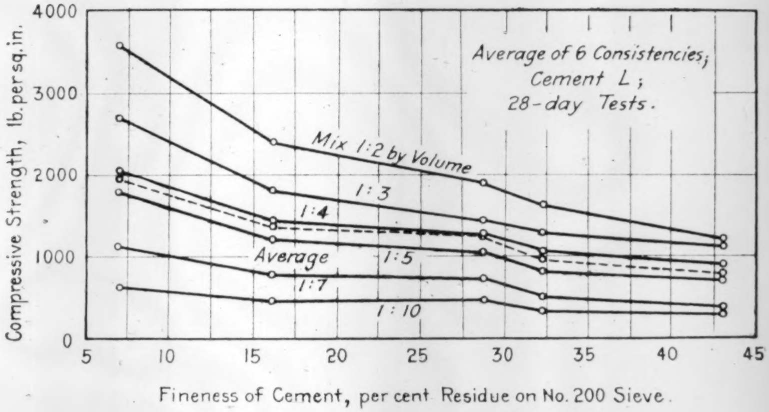

FIG. 29.—Effect of Fineness of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. See Table XXIII.
Cement L. Average of 6 consistencies. Compare Fig. 26.
Similar diagrams may be platted for other consistencies.

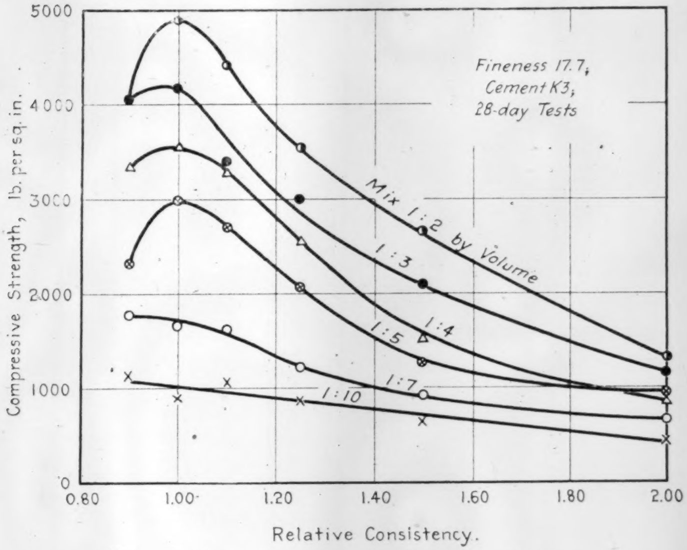

FIG. 30.—Effect of Consistency on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. Cement K-3. See Table XXIII.
Similar diagrams may be platted for the other cements in this series.

the apparatus shown in Fig. 4. The tests included cements of five different finenesses, six different mixtures, and six different consistencies. Specimens were first stored in damp sand, followed by periods of air and water storage. The results of the tests are given in Table XXXV. Concrete of all mixes and consistencies showed expansion in damp sand and water storage and contraction in air. The change in length is practically independent of the fineness of cement and is influenced only slightly by the mix. The richer mixtures show somewhat less change in length than the leaner ones. The consistency of the concrete had little or no influence on the expansion or contraction.

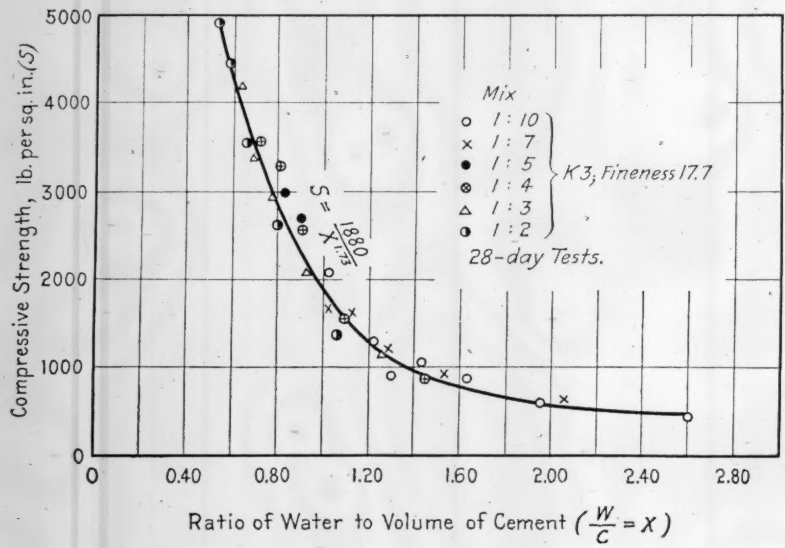

FIG. 31.—Water-ratio - Strength Relation for Cement K-3—Series 120.

Compression tests of 6 by 12-in. cylinders. See Tables XXIII and XXV. Similar diagrams may be platted for the other finenesses of cement K.

Yield and Density of Concrete.—Yield and denisty of concrete were calculated for tests in Series 118 and 120; see Tables XXII, XXXII to XXXIV. The yield is computed on the basis of the original volume of the mixed aggregate, the unit weights of aggregate being determined by the method described above.

The yield is not appreciably affected by the fineness of the cement. It is clearly influenced by both consistency of the concrete and the mix. For usual mixtures and consistencies this method gives yields only a little higher than the volumes of the aggregate. For 1:5 mix of aggregates graded to 1½ in. (Tables XXXII and XXXIII) we find a yield of about 1.05. For similar very wet mixtures the yield is increased to about 1.12. The yield is increased for the richer mixtures and for aggregates of small sizes.

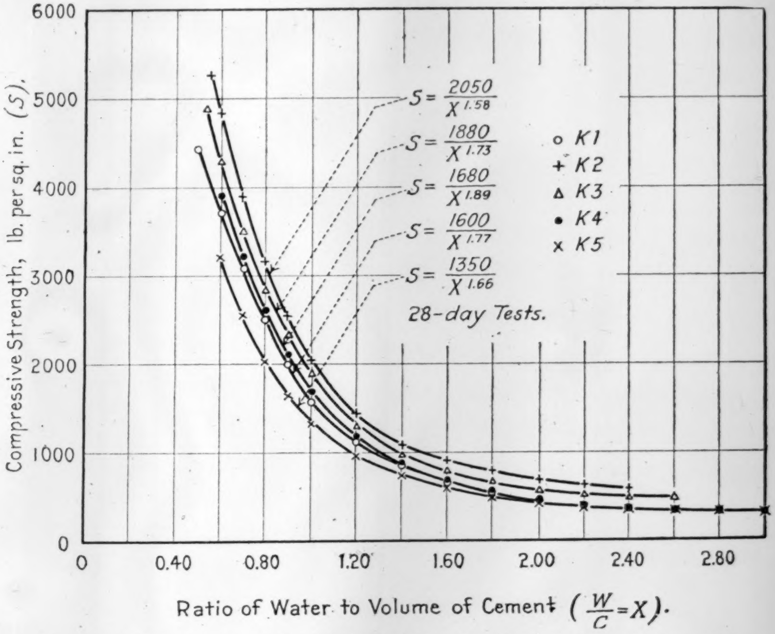

FIG. 32.—Water-ratio - Strength Relation for Cements K—Series 120.

Compression tests of 6 by 12-in. cylinders. See Tables XXIII and XXV. Curves constructed from diagrams similar to Fig. 31.

The density of concrete is computed on the basis of the total volume of solids in the mass. For ordinary mixtures, such as 1:5 or 1:4, for usual consistencies, the density is about 0.82. The density is decreased by wet consistencies or aggregates of small size. Maximum density is found with mixtures of about 1:7.

Slump Tests for Workability.—The slump tests were carried out on all specimens in Series 118 and 120. The apparatus used in making this test is shown in Fig. 1. The data from slump tests on these series are given in Tables XXI, XXX and XXXI. Each value is the average of three to five determinations made on different days. The values for the 1:1¾ mixes in Series 118 are platted in Fig. 24. The slump is greatly increased for the wetter consistencies, but the fineness of the cement has little influence. It will be noted that the water proportioning was not exactly correct, since the curve for a relative consistency of 1.00 should have been horizontal, whereas it shows a slight inclination.

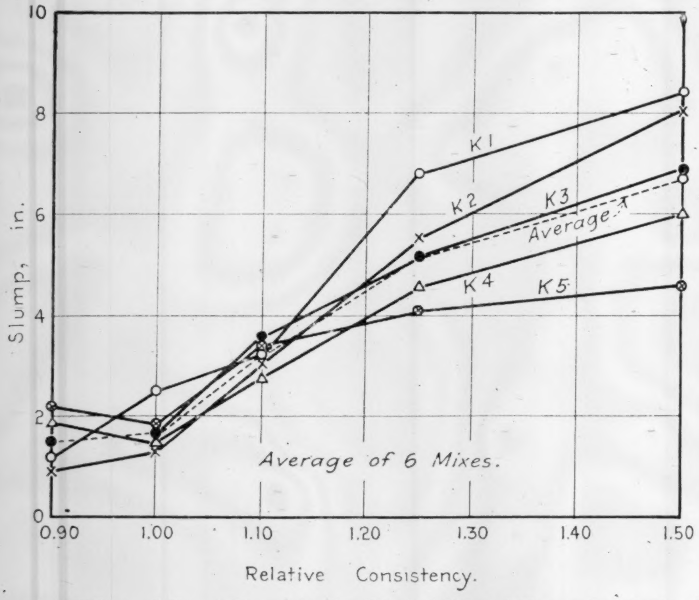

FIG. 33.—Effect of Consistency on the Workability of Concrete—Series 120.

"Slump" tests of 6 by 12-in. cylinders made with apparatus shown in Fig. 1. Cement K. See Table XXXI.

Each value is the average of 30 tests from 6 mixes.

Slumps for the tests in Series 120 are given in Fig. 33. It should be noted that these curves are based on the average of six different mixtures. The tables show that the leaner mixtures and the wetter consistencies are more affected by fineness of grinding of cement than are the mixtures of usual composition. In general, it may be said that for the richer mixtures and the consistencies usually used in building construction the fineness of the cement has no appreciable effect on the workability of concrete as determined by the slump test.

Unit Weight of Cement.—The unit weight of cement was greatly changed by the fineness of grinding. Fig. 20 gives the relation between the weight and fineness for cements K and L. The finer the cement the less the unit weight. For the cements used in these tests unit weights varied from 76 (residue 2.4 per cent) to 108 lb. per cu. ft. (residue 43.3 per cent). The different cements gave quite similar results in this respect. For the usual range in fineness the weight is lowered $\frac{3}{4}$ lb. per cu. ft. for each 1 per cent decrease in residue on the No. 200 sieve. It should be noted that in using 94 lb. per cu. ft. as a

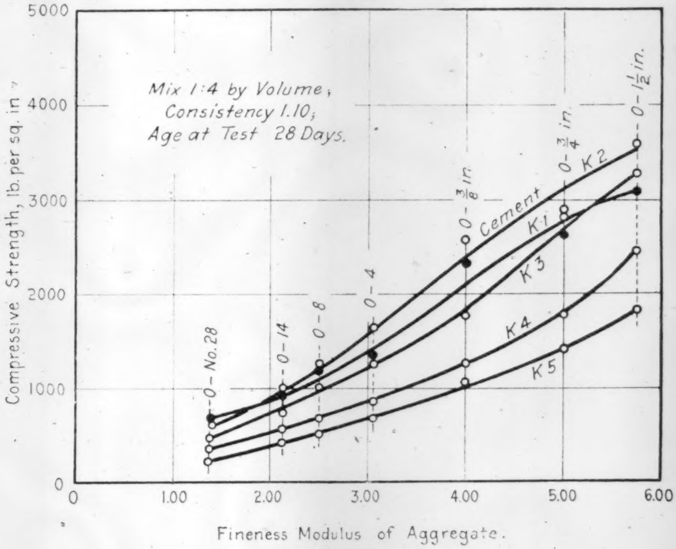

FIG. 34.—Effect of Size of Aggregate on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table XXVI. Similar diagrams may be constructed for the 7-day and 3-month tests.

uniform basis for proportioning, as was done in all the tests included in this report, the *volume* of the cement in the batch varies as much as 35 per cent. If the concrete had been proportioned in a manner to give a uniform *volume* of cement the comparisons would not have been so favorable to the finer cements. It is interesting to note that early cement specifications were based on the theory that the heavier cement was superior, yet at the same time they insisted on fine grinding. These two requirements are, of course, contradictory.

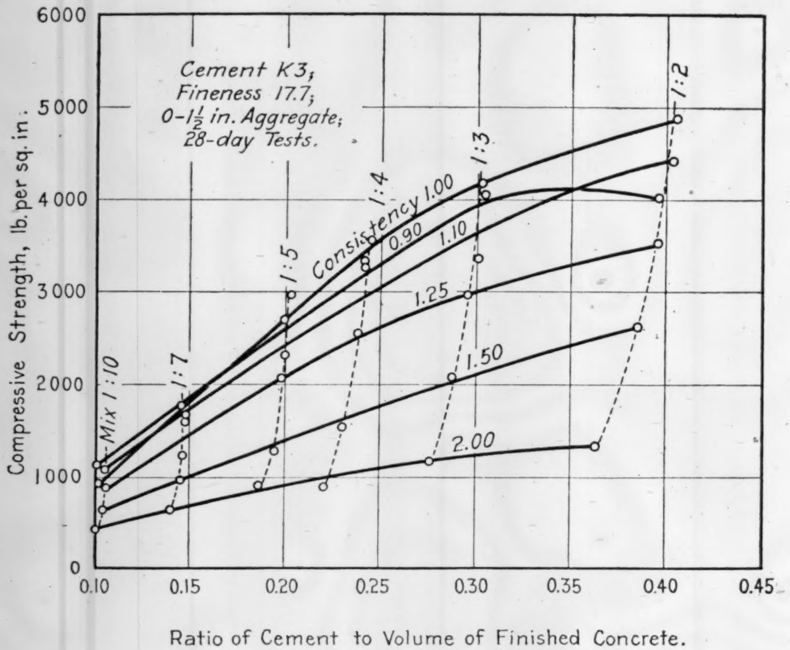

FIG. 35.—Effect of Quantity of Cement on the Strength of Concrete—Series 120.

Compression tests of 6 by 12-in. cylinders. Cement K-3. See Table XXIII. Similar diagrams may be constructed for the other finenesses of cements K and L.

Normal Consistency of Cement.—The normal consistency of cement (by weight) is increased with fineness. The different cements gave quite similar results in this respect. The normal

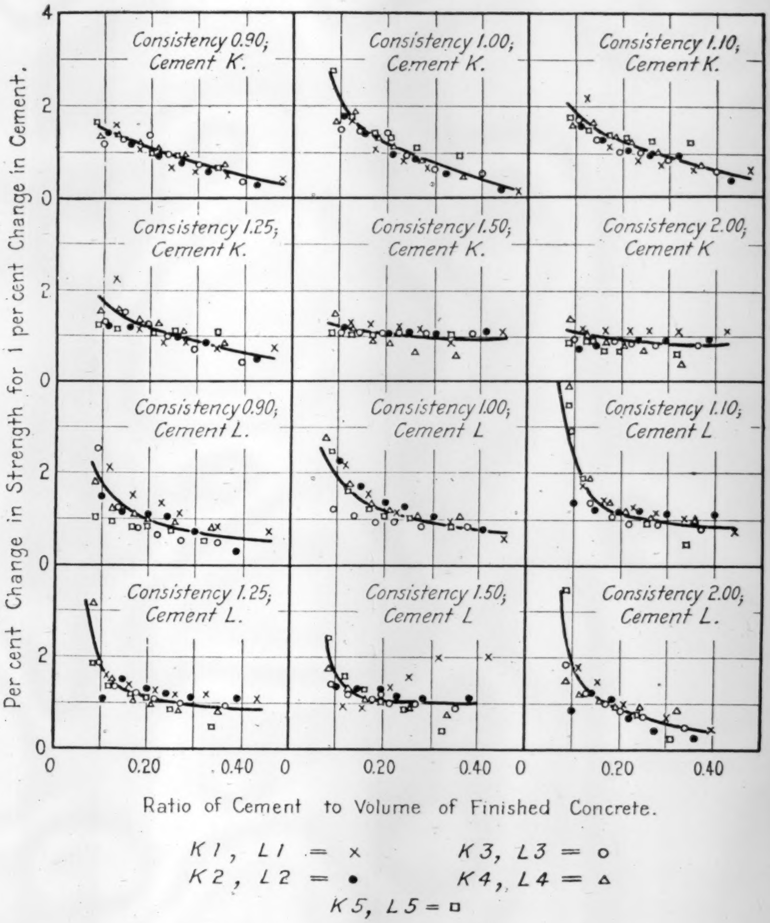

FIG. 36.—Change in Strength of Concrete with Quantity of Cement—Series 120.

Compression tests of 6 by 12-in. cylinders. Compare Figs. 13 and 14.
Cements K and L. Age at test 28 days.
Values determined from curves similar to those in Fig. 35.

consistency is increased about 0.1 per cent (in terms of weight of cement) for each 1 per cent reduction in residue on the No. 200 sieve. The normal consistency *by volume* is only slightly increased with the fineness of grinding. Normal consistency by volume is the same as the water-ratio for neat cement.

Time of Setting of Cement.—The study of the effect of fineness on the time of setting of cement may be made from the results given in Table IV. The Vicat needle tests for initial sets were somewhat erratic; however, the results clearly show a marked reduction in the setting time with the finer grinding of cement. In some instances the time of set is reduced to such an extent that the cement probably could not be used in construction work.

Type of Aggregate.—Three distinct types of aggregate were used in these experiments. The bulk of the tests were made with sand and pebbles. Tests in Series 118 included aggregates consisting of burnt shale slag and crushed blast-furnace slag. The effect of fineness of cement appears to be independent of the nature of the aggregate.

SUMMARY AND CONCLUSIONS.

A summary of the investigations and the principal conclusions are given at the beginning of this paper.

DISCUSSION.

MR. P. H. BATES.—May I ask what is the weight per cubic foot of the very fine cement? **Mr. Bates.**

MR. D. A. ABRAMS.—The finest cement weighed about 76 lb. per cu. ft. and the coarsest 108 lb. per cu. ft. This gives an extreme variation of about 35 per cent in the unit weight of the cements. It should be pointed out that the same variation exists in the volume of cement in the specimens. The quantity of cement, regardless of fineness, was determined on the basis of 94 lb. per cu. ft. Since cement is sold by weight, that seems to be the proper basis. The benefit of finer grinding would have been less apparent if the cement had been proportioned by volume. In some respects finer grinding may be considered only a very costly method of increasing the volume of a given weight of cement. **Mr. Abrams.**

MR. BATES.—May I inquire whether the fact that the very finely ground cement, having a very light bulk weight, does not explain the low strengths? As the concretes were proportioned by volume, necessarily those made from the fine cement contained less cementing material. Also, as some of the fine cement set in five minutes, it is possible that the concrete made from these had acquired partial set before the molding was completed. **Mr. Bates.**

MR. ABRAMS.—The difference in volume of cement does not explain the low strengths of some of the finest cements. All concrete mixtures were proportioned as if the cement weighed 94 lb. per cu. ft. The concrete from the finest cements contained as much as 35 per cent more cement *by volume* than the same mix from the coarsest cements; consequently the conditions with reference to the volume of cement in the specimen were just opposite to that suggested by Mr. Bates. The concrete mixes may be described more correctly as 94 lb. of cement to a given number of volumes of aggregate. Strictly speaking, the proportions were by volume only for the cements of approximately standard fineness. **Mr. Abrams.**

Cement in concrete sets more slowly than in neat cement mixed to normal consistency, due to the higher water ratio of

Mr. Abrams. the concrete. There was nothing to indicate that setting had begun before molding was completed. The specimens were molded 5 to 10 minutes after water was added.

It should be noted that Cement K, which showed a falling off in the concrete strength for the finest sample (Figs. 21, 22, 25 to 28), did not show extremely rapid setting. On the other hand, the finest samples of Cement F which gave initial sets with Vicat needle at 5 and 7 minutes (Table IV) showed a normal increase in concrete strength for all mixes (Fig. 8).

Mr. Enright. MR. BERNARD ENRIGHT (*by letter*).—It is hardly necessary to draw attention to the value of the splendid line of tests presented in the paper of Mr. Abrams. While a great many of the points developed have been known to other investigators, by reason of private research, for a long time, the tests presented so admirably cover these as to at once carry conviction.

As stated, "there is no necessary relation between the strength of concrete and the fineness of cement, if different cements are considered." The last five words cover the case in a nutshell.

Tension tests are not as valuable as compression tests of the mortars and concretes, and regardless of differences of opinion concerning the latter, the comparative results obtained by using the same method in all tests serve to make conclusive the points developed.

It has long been realized by the practical technical cement manufacturer that the fineness to which the raw material is ground, while only one factor governing quality, is nevertheless far more important, in this connection, than the fineness of grinding of the resulting clinker.

Mr. Pearson. MR. J. C. PEARSON (*by letter*).—One cannot fail to be impressed by the enormous amount of work represented in this paper. In the opening paragraphs attention is called to the fact that the data contained therein are based upon more than 20,000 tests—enough, it would seem, to very thoroughly cover the field. One may therefore well hesitate, especially in view of the very short time available for studying the report, to offer any criticism of the results obtained, or to suggest that certain things might have been done which were left undone. But because the subject is one of particular interest to the writer he

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would like to put into the record certain comments, the main purpose of which is to indicate that a number of very important lines of research in connection with the fineness problem still remain open, and that some of the conclusions in this paper will bear further investigation.

Mr. Abrams' purpose was undoubtedly to cover the range of fineness in cements typical of the commercial product as developed up to the present time. The general conclusion in regard to strength is that for cements up to 90 per cent passing the No. 200 sieve, strength increases regularly with the fineness. Cements of higher fineness than 90 per cent were found to be erratic, in most cases showing a reduction in strength. The question immediately arises, is this a true phenomenon, or is it that the conditions of the tests were not such as to indicate the real value of the material? It is well known that cements ground to high fineness tend to become quick setting, and that both the manipulation of the mix and the chemical composition of the cement need adjustment if best results are to be obtained. Hand mixing of concrete with a trowel in a pan is at best a questionable method of mixing, and the finer the fine material in the mixture the more questionable the method becomes. Something has been learned, also, during the last two years about the necessity for proper balance in chemical composition in cements which have to meet a 90-per-cent fineness requirement. Some years ago when the air analyzer for determining the fineness of cements in the region beyond the reach of mechanical sieves had been put into operation, the writer made up ten 2 by 2-in. cylinders of 1:6 standard sand mortar from five fractions of the same cement as indicated in the following table:

Specimen No.	Fractions of Normal Cement.	Compressive Strength, lb. per sq. in.	
		7-day.	28-day.
1 and 2	Normal (100%)	601	1117
3 and 4	Passing 200 mesh (79%)	859	1156
5 and 6	Passing 350 mesh (65%)	808	1301
7 and 8	Passing 500 mesh (50%)	1603	2240
9 and 10	Passing 1000 mesh (30%)	2229	2451

Mr. Pearson. Nos. 5 to 10, inclusive, were made from a few precious ounces of cement laboriously separated by means of the air analyzer, the fractions containing particles of such size that they would pass sieves of the designation indicated, if such sieves were in existence. The results of the compression tests indicate that the early strength of cement lies chiefly in the very fine material, and if research were carried into a region far beyond that covered in Mr. Abrams' report, we might still expect to find an increase in strength with fineness, *provided only, however, that the changed conditions under which we are working are met by proper physical and chemical adjustments.*

Another question which arises in a brief study of the paper is the usefulness of the slump test as a measure of consistency or workability of concrete. This test first came into general use in connection with work for the Concrete Ship Section of the Emergency Fleet Corporation, and because it served a very useful purpose in indicating the quantity of water required in gaging the rich mixtures then under investigation, it was quickly applied to other and leaner mixtures typical of those used in ordinary building construction. In the work at the Bureau of Standards it was soon found that the slump test could not be relied upon for gaging mixtures leaner than 1:1½:3 or 1:2:4, and while the average results of a large number of tests on similar mixtures might be fairly concordant, the individual results, a limited number of which only could be made on a given batch, were too variable to warrant using the test at all. Mr. Abrams' own figures indicate similar experience; for example, in Table XXXI the following slumps were observed for cement K-1 as a basis for so-called "normal consistency" in mixtures of cement, sand and pebbles:

MIX BY VOLUME.	SLUMP, IN.
1:10	1.4
1: 7	0.4
1: 5	8.5
1: 4	0.9
1. 3	2.8
1: 2	0.8

It is to be noted that these slumps, varying from 4 to 85 per cent of the total possible slump, are each the average of

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five determinations. (To those who are not familiar with these tests, the artist's drawing, Fig. 2, is likely to be misleading.) It follows from the foregoing that no high degree of confidence can be placed in the consistency designations, 0.90, 1.00, 1.10, 1.25, etc., used throughout this report, for if the normal consistency determinations are in error, the others must also be in error.

The point of the foregoing criticism is that there has not yet been developed any adequate means of determining the amount of water to be used in gaging concrete mixtures for comparative tests. A device of the jig-table type is now used for this purpose in all concrete tests at the Bureau of Standards, which has an advantage over the slump test in giving much more consistent readings on the leaner mixtures, and within the range of working consistencies, of giving readings which are proportional to the percentages of water used. We now consider this device essential to all our testing and investigative work, but it is not yet so perfect an instrument as to preclude further improvement, nor the possible development of a still more effective instrument for determining what may be called "normal" or any other pre-determined consistency of a concrete mixture. In the opinion of the writer this problem is of extreme and fundamental importance, for upon its solution depends the satisfactory performance of every day work in the testing laboratory, not to mention the more exacting requirements of investigative work.

A third question which might be raised is in regard to conclusion No. 9: "For the richer mixtures and the consistency necessary for building construction the fineness of the cement has no appreciable effect on the workability of concrete as determined by the slump test." This is a very important conclusion if true, and one which should be of particular interest to those who advocate the use of small percentages of hydrated lime and other finely divided materials in concrete mixtures to increase their workability. The writer is not prepared to express a positive opinion on the subject, but would like to review the evidence as presented in Fig. 24 of this report. Unfortunately not enough data are given in the paper to indicate clearly how the curves in Fig. 24 are derived, but the writer assumes that

Mr. Pearson. the normal consistencies of the mixtures containing the cements of different fineness were gaged in such manner as to yield a slump of ½ to 1 in. (This is in accord with the definition of normal consistency given in Mr. Abrams' paper "Design of Concrete Mixtures.") It is important to note here that the *effect of fineness*, whatever it is, does not appear in the normal consistency mixtures, and there is, of course, no conclusion to be drawn as to the effect of fineness on the workability of these mixtures. As for the other mixtures, 5, 10, 15, etc., per cent more water was apparently added to the amount required for normal consistency in each case, and by observation of the resulting slumps, the data for the series of curves were obtained. The diagram seems to tell us, therefore, that the author started with a constant normal consistency and found the wetter consistencies to be variable. This is confusing, because one has been led to think of consistency as something definitely determined by the slump test, whereas we now have different slumps for the same consistency. And finally, one wonders to what extent these results indicate real differences in the mixtures, and to what extent they depend upon the limitations of the slump test.

Perhaps the foregoing is the wrong interpretation of Fig. 24; in any event, the writer believes that the word "workability" as used in the statement of conclusion No. 9 is likely to be misunderstood. Is it not conceivable that "consistency" and "workability," presumably of the same meaning as Mr. Abrams uses them, may be quite different in their real significance? Cannot two concrete mixtures, one rich and plastic, the other lean and harsh, be gaged approximately to the same consistency as indicated by the slump test, or by the flow table, and yet be quite different in *workability?* In this sense Mr. Abrams' conclusion in regard to the workability of concrete as dependent on the fineness of cement is not justified, for neither the slump test nor any other test in common use is capable of indicating what part of the workability of a mixture is contributed by the solids and what part by the mixing water. The time will probably come when we may expect to have for concrete mixtures a definite measure for consistency, meaning by this some device which will indicate when the proper amount of mixing water has been added, and another measure for workability, meaning by this

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some device which will indicate how much work will have to be done upon one mixture in comparison with another in getting them into place. This is by no means an imaginary problem; the producers of hydrated lime, diatomaceous earth and many other materials are keenly interested in it, and some honor should be due the investigator who first suggests a rational method of solving it.

In conclusion the writer would like to express an opinion regarding the usefulness of the "water ratio" in its relation to the strength of concrete. This relation is expressed by the equations

$$S = \frac{A}{B^x} \text{ and } S = \frac{D}{X^a},$$

the curves which they represent being of similar form within the limits of normal working consistencies established by the author's experimental work. In numerous attempts to check the validity of these equations, both from old and new work, we found the averages of many widely varying results to lie in zones having the general sweep of these curves. From this study the conclusion has been reached that either of the equations involving strength and water ratio as variables is an expression of a tendency only, and cannot be relied upon for more than a rough estimate of concrete strength, even after preliminary trials are made with given materials. The failure of these equations to apply to all sorts of concrete, particularly to those concretes containing large proportions of carefully graded aggregates, is a most serious objection to them as expressions of a general law. In mixtures of this type the method of handling makes a very great difference in the strength of the resulting product, and we find the unspecified factor of workmanship entering, not only as an important consideration in the determination of quality, but in many cases as the controlling factor. It is difficult to see how the quality of workmanship is to be expressed mathematically, and for this reason the writer believes there is little hope of arriving at any final and definite law for the proportioning of concrete mixtures. The "water ratio" theory, the "surface area" theory, and numerous other theories may be very useful as mental references to indicate approximately what order of

Mr. Pearson. merit may exist in this or that combination, but no general law that *does not involve the making of the concrete* can apply to the entire range of concrete mixtures.

Mr. Young. MR. R. B. YOUNG (*by letter*).—In the Laboratories of the Hydro-Electric Power Commission of Ontario with which the writer is connected, we have made repeated attempts to use the slump test for consistency as described by Mr. Abrams in this paper. Our efforts have not been crowned with any great success. The method has serious limitations.

Our experience covering several thousand tests has led us to the conclusion that the method will not apply to concrete mixtures in which crushed rock is an aggregate. With sand and gravel mixtures very satisfactory results may be obtainable, but with sand and crushed rock or sand gravel and rock mixtures the test is not indicative of the relative workability of the concrete. With sand and gravel and crushed rock mixtures the test specimens will slump little if at all until they become so plastic as to collapse. The form of this collapse is usually a side slip of the top portion of the test cylinder and quite different from the settling obtained using gravel mixtures. Our experience covers a wide range of these sand gravel and crushed rock combinations, both very lean and very rich, with aggregates from several different sources.

Criticism should be constructive, not destructive, and we are in the unfortunate position of being unable to offer a method of testing consistency not subject to defects equal to or greater than those of the slump test. It is a matter of the greatest importance that some definite method of defining and measuring the mobility of concrete mixtures be developed and adopted by this Society. The lack of such a standard of mobility makes the study of the laws underlying the latter very difficult and gives rise to much confusion and misunderstanding.

We note Mr. Abrams has adopted an equation of the form $y = \frac{a}{x^b}$ instead of $y = \frac{a}{b^x}$ to express the relation between water ratio and compressive strength. In experiments we have made we found that while a curve having an equation of the latter type would fit a series of tests of limited range, it did not fit the data of those series which included both very rich and very lean concretes, while a curve of the former type would fit such a series very closely. **Mr. Young.**

We wish to emphasize Mr. Abrams' statement that he finds briquette tests are "erratic and cannot be interpreted as showing the same relation as found in the concrete investigations" while "compression tests of mortar in general confirm the results of the concrete tests." Many erroneous conclusions have been drawn in the past from small scale experiments using briquette specimens. Many engineers, even some test engineers, do not fully appreciate this even yet. We have found compression tests of mortar very satisfactory and we use them for most preliminary work and for minor investigations of materials where the expense of concrete tests is not warranted.

Mr. Abrams. MR. ABRAMS (*Author's closure by letter*).—These studies of the effect of fineness of cement were carried out during a period when our ideas with reference to methods of testing concrete and the interpretation of such tests were undergoing many changes. Some of these changes can readily be traced in the tests reported in this paper. A few instances may be mentioned:

1. In earlier work emphasis was placed on tension and compression tests of mortar; later work was largely confined to compression tests of concrete.

2. It has been the practice heretofore to study the effect of fineness of cement by means of tests on two samples differing only a few per cent in residue; in our tests a graduated series of finenesses (generally five to seven) was used, thus enabling us to determine the trend in values for any ordinary range in fineness.

3. The method of proportioning using one volume of cement to a given number of volumes of aggregate is considered an improvement over the old method of arbitrary proportions (such as 1:2:4).

4. The fundamental rôle of "water ratio" in determining the strength of concrete was established during the period covered by these tests.

5. The importance of the workability of concrete and the limitations of this factor on the problem of proportioning was recognized in the later tests, but was not fully appreciated in the earlier series.

6. The practice of making concrete specimens from separate

Mr. Abrams. batches and basing conclusions on averages of five or more specimens made on different days is an important advance over the older method of making all the specimens of a given mix from a large batch of hand or machine-mixed concrete. Our method tends to eliminate many accidental variations in mixing, molding, curing, etc., which may affect the quality of concrete in a single batch.

7. The effect of fineness of cement must be determined by a study of the trend of values for concrete of the widest range of mixture, consistency, size and grading of aggregate, age, etc.

While it is believed that the conclusions stated are fully established by the tests, the writer would be the first to agree with Mr. Pearson that there are a number of important lines of research which remain for further investigation.

With reference to the erratic results given by the extremely fine cements, mentioned by Mr. Pearson, it is not clear how tests could have been made which would more nearly indicate the true value of the material. It is inconceivable that we should find a falling-off in the concrete strength for the finest sample of Cement K in nine different consistencies for each of two different mixes (Figs. 21 and 22) and for six consistencies of each of six different mixes (Table XXIII and Figs. 25 to 28) and for three different ages (Table XXIV, and Figs. 27 and 28), if this does not represent the true phenomenon. Cement F, in which a wide range in fineness was used, showed a normal increase in strength of both concrete and mortar for the finest samples for all mixes, consistencies and ages (Tables XIII and XIV and Fig. 8). On the other hand, cement L showed an abnormally high strength for the finest sample (residue 7.2 per cent) for all mixes, consistencies, ages, etc. (Table XVII and XVIII and Fig. 29). Cement G also gave abnormally high strengths for the finest sample (Tables XIII and XIV). In view of these results it seems proper to conclude the "the cements with residues below about 10 per cent were inclined to give erratic results in the strength tests." The reason for this is not clear, since each lot of the cements under consideration was ground from the same clinker. The chemical analysis shows no variations which would account for the differences in the behavior of the finest samples. It seems that extreme fineness introduces factors which are not now understood and not readily controlled.

Mr. Abrams.

In answer to Mr. Pearson's comment concerning time of setting of cement, reference may be made to my remarks above in answer to Mr. Bates' question. The cements which showed abnormally rapid sets were not the ones which showed low strengths, as might appear at first thought.

The writer fails to understand Mr. Pearson's objection to hand mixing of small batches of concrete in research work. What we desire is a method of proportioning and mixing which will leave no doubt as to the actual quantity of materials in each specimen and give uniform strength in duplicate tests. It is difficult to mix large batches by hand or by machine in such a manner as to secure this result. Our tests have shown that with proper care concordant results can be secured with certain mixers from different specimens in a batch of machine-mixed concrete. There is frequently a wider variation in the quality of concrete in successive batches, probably due to unavoidable errors in proportioning the batch, time of mixing, discharge, etc. The mean error of tests on specimens mixed separately by hand on different days, compares favorably with that of duplicate specimens from the same batch of machine-mixed concrete.[1] Batches of machine-mixed concrete, mixed on different days, frequently show wide variations. In most instances only a small quantity of concrete is required; this suggests hand mixing. Many mixers in discharging hold back the finer materials in the batch, which makes it impossible to use them for research purposes. Hand mixing in small batches where the entire batch is used in a single specimen leaves no doubt as to the exact quantity of cement, aggregate and water used in each specimen. It is the writer's opinion, based on nearly fifteen years' experience in experimental studies of concrete, that the practice of hand-mixing concrete in small batches and basing conclusions on the results of several such tests made on different days is one of the most important improvements which have been made in the technique of concrete testing in recent years. If it is desired to compare the results of hand-mixing with the performance of a machine mixer, that can readily be done. The results of such a comparison are published in the writer's

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[1] See Abrams, "Effect of Time of Mixing on the Strength and Wear of Concrete," *Proceedings*, Am. Concrete Inst., Vol. XIV, p. 87 (1918).

Mr. Abrams. report on "Time of Mixing" referred to above. These tests showed that our standard method of hand mixing gives the same strength as similar concrete mixed for 1½ minutes in the mixer used. The results did not vary much for a wide range of mixes and sizes of aggregate; for the mixes made up from fine sand only as aggregate, hand mixing was equivalent to 2 to 5 minutes of machine mixing.

The writer might paraphrase Mr. Pearson's statement and say, "To base conclusions as to the properties of concrete on the results of 1:6 mortar tests on a few ounces of cement is questionable." It would be interesting to know whether differences in the water requirements of the cements were taken into account in making the tests. Variation of a few drops in the water used might account for the differences in strength given by the cements of different finenesses. The excessive aeration received by cements discharged by the air analyzer would make conclusions based on such tests more questionable.

The slump test for consistency has been in use in this Laboratory for several years. It is the writer's impression that it was first suggested by Mr. Sanford E. Thompson about 1913 in outlining certain tests for a committee of the American Concrete Institute. This test allows the specimen to deform under the action of a constant force represented by the head of concrete. The jigging method used by the Bureau of Standards is different, but it is not clear that it is any better. A certain element of impact is present in the latter method which must be very difficult to measure or standardize. The fact that the jigging-table method cannot be used outside the laboratory would seem to be a fatal limitation to its usefulness. The slump test can be used in the field, since a satisfactory indication of relative consistency can be secured by withdrawing the form by hand. This test has been extensively used during the past season by the Highway Departments of Illinois and other states in concrete road construction. While a single determination should not be interpreted too strictly, it furnishes a ready means of checking the tendency to use too much water. It is true that the slump test is likely to give erratic results in lean mixtures, but such mixtures are comparatively unimportant in concrete work.

In view of Mr. Pearson's comments, an explanatory note has been added to Fig. 2. It is not clear how this figure can be misleading, since it is a faithful reproduction from a photograph of actual specimens. The original photograph was not satisfactory for reproduction on account of lack of contrast in color as between the concrete and the background. **Mr. Abrams.**

The relative consistencies referred to in the report were intended only as a short-hand method for indicating a graduated series of water contents. The actual quantity of water is given in the tables, consequently there can be no misunderstanding.

Mr. Pearson says, "Unfortunately, not enough data are given in the report to indicate clearly how the curves in Fig. 24 are derived . . . ." It would seem to be impossible to give more data. The notes immediately below the legend give the mix, aggregate and the cements used and refer to Table XVI where the results of the slump test are printed. The properties of the cements and aggregate and the quantities of water used are given in other tables. The quantities of water used in all of these tests were predetermined by calculation. However, it is seen that the slumps for the normal consistency mixes (relative consistency, 1.00) actually do fall within the limits set, that is, ½ to 1 in. There is a slight progressive decrease in slump as we approach the coarser cements. This means simply that our "water formula" was not quite exact, but still does not give results which fall outside the limits set by our definition. This slight error can easily be corrected by redrawing the curve for normal consistency to a mean horizontal position and rotating all other curves accordingly. If this were done it would tend still further to remove any advantage which finer grinding of cement may be assumed to possess in increasing the plasticity of concrete.

In predetermining the quantity of water required by means of our water formula we take into account the following factors:

1. The workability of the concrete,
2. Quantity of cement (the mix),
3. Normal consistency of the cement,
4. Size and grading of aggregate (fineness modulus),
5. Absorption of aggregate, and
6. Water contained in aggregate.

Mr. Abrams. The water formula used was as follows:

$$x = R\left[\frac{3}{2}p + \left(\frac{0.30}{1.26^m} + a - c\right)n\right]$$

where x = Water required, ratio to volume of cement in batch (water ratio);

R = Relative consistency of concrete, or "workability factor";

p = Normal consistency of cement, ratio by weight;

m = Fineness modulus of aggregate (an exponent);

n = Volumes of mixed aggregate to one of cement;

a = Absorption of aggregate, ratio of water absorbed to volume of aggregate (determined after immersion in water for 3 hours); and

c = Moisture contained in aggregate, ratio of water contained to volume of aggregate.

The difference in water requirements of different cements *due to fineness or any other cause must be taken into account before we can make any comparisons of the resulting concrete on the basis of workability or any other factor.* Our water formula gives to the finer cements a slight excess of water, the exact amount being proportional to the difference in normal consistencies determined by the Vicat needle. The quantities of water used in these tests are given in Table XIX. It should be noted that the water ratios here reported are based on the *actual volumes* of cement, whereas the cements were proportioned by weight (94 lb. per cu. ft. in all cases). If these water ratios are recalculated on the basis of a uniform weight of cement (which is the basis for standard determination of normal consistency) it is seen that the only difference for a given mix and consistency is due to the variation in normal consistency of the two cements.

The fact that with water proportioned in this manner we get practically uniform slumps for concrete made from two different cements as shown in Fig. 24, is sufficient evidence of the correctness of the water formula. In view of the method used it is obvious that Mr. Pearson is in error in concluding that the effect of fineness does not appear in the normal consistency mixes. It does appear and is as shown in Fig. 24, or strictly, as

Mr. Abrams.

this figure would appear if all the curves were rotated to such an extent as to make the line for "relative consistency 1.00" horizontal as described above. In these tests the finer cements received more water than the coarser samples, whereas most experimenters would probably have used the same quantity for all cements. In other words, our method of proportioning water tends to favor the finer cements so far as workability is concerned.

The whole question with reference to the terms "consistency" and "workability" is entirely one of definition and methods of determining these factors, as in the case of other physical terms and constants. As stated in the paper we have used "consistency" as applying to the plastic condition of the concrete without reference to the actual quantity of water present. Consistency is based on the evidence of the slump test. In this sense "consistency" may be considered as a measure of workability. Of course, others may prefer other definitions of these terms and to use other methods of measuring these properties. The water ratio refers to the actual quantity of water as compared to the cement and takes no account of the plastic condition of the concrete. Both of these conceptions are useful in dealing with concrete mixtures.

The water ratio strength relation as expressed by the equations quoted by Mr. Pearson and illustrated in Fig. 31 and 32 have been found to hold in every series of tests carried out in this laboratory where the quantity of water used was changed for any reason, so long as the fundamental principles of concrete making are not violated; that is, so long as the aggregate is not graded too coarse for the quantity of cement used, and the concrete is plastic. These laws have been found to hold for the tests in each of 22 different series made over a period of four years, by different men, using many different cements and aggregates and for both hand and machine-mixed concrete. Examples of such tests have appeared in nearly every report issued by this laboratory. It is obvious that methods of handling and workmanship are important factors in determining the strength and other properties of concrete. However, it is the writer's belief that all such factors which have a bearing on *changing the water content* exert their influence solely due to such change; for example, it has recently been shown that the effect

Mr. Abrams. of pressure on fresh concrete is measured by the quantity of water forced out.[1]

The tests platted in Fig. 31 do not indicate that that curve is the "expression of a tendency only," as stated by Mr. Pearson. Dozens of other curves of the same nature may be platted from data contained in the tables. The writer knows of no instance in which properly made tests of concrete fail to follow this law; if concrete tests do not follow this law it is probably due to faulty test methods. The writer has never claimed that this law takes account of all factors involved in the making of concrete. However, thousands of tests made in this laboratory have proven conclusively that for given materials, methods and conditions the water ratio of the concrete is the determining factor.

We have not used the slump test as extensively with crushed aggregate as with gravels; however, such tests as have been made have not given the results stated by Mr. Young. My paper shows the results of many slump tests using crushed burnt shale aggregate which is quite angular. With a deficiency of fine material in the mix the crushed stone concrete would no doubt give the effect described by Mr. Young.

The writer agrees that there is room for improvement in the present slump test. Other methods are now being tried. Mr. F. L. Roman, Testing Engineer of the Illinois Bureau of Highways, has suggested the use of a form made in the shape of a truncated cone with 4-in. top diameter and 8-in. bottom diameter for the slump test.

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[1] *Proceedings*, Am. Concrete Inst., XV, 1919; or *Bulletin No. 3*, Structural Materials Research Laboratory.

CEMENTS PRODUCING QUICK-HARDENING CONCRETE.[1]

By P. H. Bates.

SUMMARY.

There have been prepared at the Pittsburgh Branch of the Bureau of Standards certain cements which have the property of hardening very rapidly. These were made in a manner no different from that used in making Portland cement. Their composition differed very materially from the composition of the latter, in that they were composed very largely of lime and alumina.

These calcium aluminates, when they are very high in alumina, do not have a very marked rapid initial set, but do harden very quickly and therefore produce high early strengths. Some of the maximum strengths were 3145 lb. per sq. in. for 1:6 gravel concrete tested in the form of a 6 by 12-in. cylinder at the end of 24 hours, 6010 lb. per sq. in. at the end of seven days, and 8220 lb. per sq. in. at the end of one year.

There is presented herewith also the results of testing some 6 by 12-in. cylinders in which the bonding material was "Sorel cement." These are cements produced by gaging light calcined magnesia with magnesium chloride solution. Such a cement develops in 24 hours a strength approximately equivalent to that developed at the end of seven days by a similar concrete made with Portland cement.

Both of these cements commend themselves for certain special uses, where a quick-hardening concrete of high strength is desired. Neither would be desirable where subjected to the continued action of water. The Sorel cement alone is on the market at the present time.

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[1] By permission of the Director of the U. S. Bureau of Standards.

CEMENTS PRODUCING QUICK-HARDENING CONCRETE.

By P. H. Bates.

Introductory.

In the course of the investigations which the Pittsburgh Branch of the Bureau of Standards has been conducting dealing with the various problems relating to Portland cement, there have been made a number of cements which are characterized by a very high early strength. This is developed when the cements are used either as mortars or concretes. These cements have been made in a manner differing in no wise from that used in the manufacture of Portland cement. However, the composition of the materials entering into their manufacture was decidedly different, limestone and calcined alumina having been used in some of the raw mixes, and in others the alumina was replaced in part by kaolin or bauxite in order to determine the effect of impurities on their general properties. While such materials have been the subject of research by others, especially Spackman,[1] their property of developing very high early strengths is not generally known. It is believed that the data presented in this paper, especially that dealing with the concrete, are the first of their kind ever presented.

The data dealing with the aluminates are augmented by some obtained in making concrete from "Sorel cement" which, as is generally known, is light calcined magnesite gaged with magnesium chloride. It has been unofficially reported that during the recent war the enemy used a concrete made of such a cement for "setting up" their large guns. As it obtains the greater part of its strength within 24 hours and as this strength equals that obtained by a Portland cement at the end of two or three weeks, the possibility of using it becomes very attractive. The data herewith presented were obtained in making a limited number of concretes, but it is believed that such data, in so far as they relate to concretes, have never before been presented.

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[1] Spackman, "The Aluminates: Their Properties and Possibilities in Cement Manufacture," *Proceedings*, Am. Soc. Test. Mats., Vol. X, p. 318 (1910).

CONCRETES MADE WITH SOREL CEMENT.

It is not intended to go into any great detail in presenting these data. For this reason, the nature and general properties of this cement will be touched upon but briefly. The fact that magnesium oxide when mixed with a solution of magnesium chloride will harden was possibly first known by Sorel in 1853. From him it has at least taken its more common name. The physical character of the oxide and the permissible impurities, the concentration of the chloride and its permissible impurities, and the nature of the hardened material have all been the subject of extended investigations. Briefly, the results show that the purer the ingredients, both oxide and chloride, the better the resulting cement. The oxide must be produced by burning a carbonate to such a temperature only that a plastic mass results when it is gaged with water. Too high a temperature of calcination produces a very inferior oxide. The nature of the hardening has never been satisfactorily solved. For a late investigation and discussion of these points and a satisfactory bibliography, reference should be made to Bulletin No. 879 of the University of Wisconsin.[1]

At the present time this cement is used in rather large quantities for making a resilient flooring which is usually referred to as "composition flooring." When so used the aggregate is composed of asbestos fiber, sawdust, inert finely ground filler as sand and coloring matter. This flooring is widely used in a monolithic form in office buildings, passenger and subway cars and interior ship decks. Recently a mortar very similar in nature to the above, excepting the omission of the fibrous material, has been rather successfully used as a stucco.

The magnesia used in the present investigation was made from magnesite mined in California. It was a mixture of two shipments from two manufacturers of flooring. Both had given satisfactory results when used in flooring mixes. No data are at hand which would enable one familiar with Portland cement to form an idea of the relative strengths which these would develop in the usual small briquette or compression specimen. The small specimens made were of a flooring composition and as such were composed of 50 per cent magnesia, 12 per cent asbestos, 10 per cent sawdust, 22 per cent ground sand and 6 per cent iron oxide, all by weight. This mixture when gaged with 52 per cent of a solution of chloride having a gravity of 1.1885 (about 23° Baumé) gave the following strengths in pounds per square inch:

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[1] Roark, "The Physical Properties of Magnesia Cement and Magnesia Cement Compounds," *Bulletin No. 879*, Eng. Exper. Station, University of Wisconsin.

Specimen.		24 Hours.	7 Days.	28 Days.	90 Days.
A	Tension	531	841	1087	1034
	Compression	2240	3795	5300	4340
B	Tension	576	900	935	1049
	Compression	2900	4240	5300	5370

The tension specimens were of the form specified in the A.S.T.M. Standard Specifications and Tests for Portland Cement. The compression specimens were 2 by 4-in. cylinders. All specimens were stored in air until broken.

The analyses of the mixed oxides and the chloride were as follows:

	OXIDE.	CHLORIDE.
Silica	5.14 per cent	....
Alumina	0.78 "	....
Iron oxide	0.57 "	....
Lime	5.69 "	0.20 per cent
Magnesia	85.01 "	9.24 "
Ignition loss	2.86 "	....
Potassium oxide	....	0.17 "
Sodium oxide	....	0.70 "
Chlorine	....	16.54 "

In Table I is shown the strength of the concrete made from this mixed oxide and also the compressive strength developed by a Portland-cement concrete using the same proportions of the same aggregates. Notwithstanding the fact that the specific gravity of the magnesia is very close to that of Portland cement (3.08 for the magnesia and 3.12 for the cement), the volume occupied by the same weight of the two differs very

TABLE I.—COMPARISON OF COMPRESSIVE STRENGTHS OF SOREL AND PORTLAND-CEMENT CONCRETES.

6 BY 12-IN. CYLINDERS. STRENGTHS IN POUNDS PER SQUARE INCH.

Proportions by Volume.	Percentage of Cement by Weight.		24 Hours.		48 Hours.		7 Days.		Per cent H_2O in Portland-Cement Concrete.	Per cent $MgCl_2$ in Sorel-Cement Concrete
	Portland.	MgO.	Portland.	MgO.	Portland.	MgO.	Portland.	MgO.		
					GRAVEL AGGREGATE.					
1 : 0.5 : 1.5	33.3	20.3	....	1740	1570	3490	2965	2910	12.1	14.7
1 : 1.0 : 3.0	20.0	11.3	....	1705	1115	2260	2020	2850	7.8	9.5
1 : 1.5 : 4.5	14.3	7.8	....	1755	680	2145	1430	2240	7.9	9.8
[a]1 : 1.5 : 4.5	....	14.3	....	2880	....	3315	....	2720	....	12.1
					LIMESTONE AGGREGATE.					
1 : ⅔ : 1⅓	35.2	21.8	....	2985	2260	3990	3930	4320	12.2	18.5
1 : 1⅓ : 2⅔	21.4	12.2	....	1940	1340	2805	2990	2970	9.9	13.7
1 : 2 : 4	15.4	8.5	....	1935	655	2330	1755	2480	9.5	12.8
[a]1 : 2 : 4	....	15.4	....	3270	....	4020	....	4320	....	13.7
					COARSE SAND AGGREGATE.					
1 : 0.5 : 1.5	34.0	20.8	....	2060	1715	2570	3270	2735	13.2	20.0
1 : 1.0 : 3.0	20.6	11.6	....	1910	545	2225	1635	2430	11.4	16.0
1 : 1.5 : 4.5	14.7	8.0	....	935	325	1695	985	1870	11.4	14.7
[a]1 : 1.5 : 4.5	....	14.7	....	2355	....	3260	....	3190	....	15.7

NOTE.—The percentage by weight of MgO in 1:0.5:1.5 and 1:⅔:1⅓ is but very little greater than the percentage by weight of Portland cement in 1: 1.0 : 3.0 and 1: 1⅓ : 2⅔, respectively.

[a] MgO proportioned by weight, making weight percentage of MgO equal weight percentage Portland cement in 1: 1.5 : 4.5 and 1: 2: 4.

materially. As the magnesia weighed but 51 lb. per cu. ft., the actual percentage by weight of the magnesia in any one concrete was decidedly less than the percentage of Portland cement. For this reason the 1 : 6 concrete was proportioned both by weight and by volume, when the magnesia was used as the cementing material. All specimens were stored in the air until broken. The gravel used was obtained from the Allegheny River and was screened between a ⅛-in. and 1½-in. screen. It contained an excessive amount of the finer sizes. The limestone was a rather soft stone screened between the ¼-in. and 1-in. screens. The "coarse sand" aggregate was sand from the Allegheny River screened between the ⅛-in. and ¼-in. screens.

As the information sought had to do alone with early strengths, specimens were made for breaking at 24 hours, 48 hours and 7 days in the case of those made with magnesia and 48 hours and 7 days when Portland cement was used.

The results show that the Sorel-cement concretes, with but two exceptions, have a strength at 48 hours greater than that obtained by the use of Portland cement in 7 days. However, it is also seen that there is in general but little increase in the strength of the former between the 48-hour period and the 7-day period. The results obtained at all periods from the Sorel-cement concrete proportioned by weight are generally higher than those obtained when the proportioning was done by volume, regardless of what the proportions were. This clearly shows that for such a light material the proportions should be decidedly different from those generally used with Portland cement. It would seem as if too much magnesia was used in the rich concretes and too little in the lean ones when the proportioning was carried out by volume.

Attention should be called to the difference in the manner in which the hardening of the two concretes takes place. In a Portland-cement concrete, the cement hardens by the action of the added water. During the process of hardening it is immersed in an atmosphere containing in a greater or less degree one of the essential elements of the process, that is, water, either as a liquid or vapor. On the other hand, in the Sorel-cement concrete the hardening takes place as a result of the action of the chloride on the oxide. The chloride is always essential but any deficiency, as for instance the use of a too dilute solution, or any marked excess, is injurious. Therefore, not only the ratios between the aggregate and the magnesia must be studied, but also the ratio between the chloride and the magnesia.

While the results do show the lack of proper proportioning of both the magnesia and the chloride, yet these poorly proportioned concretes show in 24 hours as high strengths as the more properly proportioned Portland-cement concretes show in seven days. Another point should be remembered in regard to these Sorel-cement concretes, that is, they cannot be frozen. Temperatures below freezing will retard the hardening to a degree, but the freezing point of the solution is so low that no care need be taken to prevent damage from low temperatures.

CONCRETES MADE WITH CALCIUM-ALUMINATE CEMENTS.

The calcium aluminates were all made in the experimental rotary kiln of the Bureau. The composition of these, the constitution arranged in order of the amounts present, and the temperatures of burning are given in Table II. The fineness and the time of setting[1] are given in Table III.

With the exception of cement No. 6, no particular difficulty was encountered in burning. On account of the composition of this cement, its position in the ternary system CaO-Al_2O_3-SiO_2 was such that it was located in a field having both a low burning temperature and also one in which the orthosilicate predominates. This combination always produces a material which fluxes at such a temperature that the silicate on cooling reverts to the γ form from the β form of the silicate. This reversion is manifested by the "dusting" of the clinker. It was possible to produce this particular cement only either in a decidedly underburned condition, or overburned to such a degree that it fell from the kiln in large, soft balls, which dusted on cooling unless quickly water quenched. The latter procedure of burning, without quenching, was used. Cement No. 4 was made from a very hard clinker but the latter did not show any tendency toward dusting. The clinker of the other cements was of the porous character of normal Portland clinker. Those low in iron oxide were white to yellowish in color; none of them had the glistening black appearance of Portland clinker, the darkest being a dark reddish brown. The raw materials used were calcined alumina and limestone for cements Nos. 1, 2 and 8; in Nos. 3, 4 and 5 the

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[1] In carrying out the investigation presented here, no addition of SO_3 in any form was made to the cements. Work carried on at the same time as this presented here showed that such additions accelerated the time of set and caused a reduction in both the tensile and compressive strength.

TABLE II.—COMPOSITION, CONSTITUTION AND TEMPERATURES OF BURNING OF CALCIUM-ALUMINATE CEMENTS.

ALL COMPOSITIONS IN PER CENT.

Cement No.	1	2	3	4	5	6	7	8
SiO_2	0.44	0.76	9.41	10.48	17.23	17.38	11.33	0.68
Al_2O_3	62.31	61.25	55.09	46.71	39.96	30.52	47.66	74.11
Fe_2O_3	0.51	0.60	2.04	2.13	2.57	1.85	3.10	0.40
CaO	36.69	36.32	30.73	39.79	38.84	46.72	34.87	23.82
MgO	0.36	0.48	2.95	1.04	1.29	2.27	3.66	0.81
Ignition loss	0.07	0.50	0.08	0.32	0.14	0.78	0.17	0.38
	100.38	99.91	100.30	100.47	100.03	100.52	100.19	100.20
Temperature of Burning, deg. Cent.	1460	1480	1490	1380	1455	1360	1445	1500
Constituents[1]	3C 5A CA 2CS	CA 5C 3A 2CS	CA 3C 5A 2CAS	2CAS CA 2CS	2CAS CA 2CS	2CS 5C 3A CA	2CAS CA 2CS	CA 3C 5A 2CAS

[1] C = CaO; A = Al_2O_3; S = SiO_2.

TABLE III.—TIME OF SETTING AND FINENESS OF CALCIUM-ALUMINATE CEMENTS.

Cement No.	Initial Set.				Final Set.				Per cent Passing 200-Mesh.
	Gillmore.		Vicat.		Gillmore.		Vicat.		
	hr.	min.	hr.	min.	hr.	min.	hr.	min.	
1	0	55	0	25	4	45	2	10	83.0
2	0	30	0	12	2	0	0	50	80.0
3	6	25	5	15	[a]		7	0	81.2
4	0	35	0	7	3	30	1	15	78.0
5	0	40	0	15	4	45	3	15	80.2
6	0	7	0	2	0	45	0	12	76.4
7	6	0	3	45	[a]		[a]		79.8
8	7	0	3	30	[a]		[a]		86.6

[a] Final Set between 8 and 16 hours.

same materials were used but part of the alumina was replaced by a kaolin, thus reducing the alumina content of the mix but increasing the silica content. In No. 6 it was necessary to add some very finely ground flint, in order to secure the desired silica content, in addition to the kaolin, alumina and limestone, and iron oxide. In No. 7 bauxite, limestone and iron oxide were the raw materials.

Reference should be made to the work of Rankin[1] and the author,[2] for further information in regard to the general properties of the constituents of these cements. For this present paper dealing more particularly with concrete made from them, it is not desirable to give more in regard to their properties than their reaction with water. Those aluminates indicated in Table II, as being present in these cements, all react with water to form the hydrated form of $3CaO . Al_2O_3$.[3] Such a reaction requires the formation of hydrated alumina. The amount of the latter will depend upon the amount of the alumina in the cement, consequently the $3CaO . 5Al_2O_3$ will give the most and the $5CaO . 3Al_2O_3$ the least. This hydrated alumina is, as is well known, a colloid and, when formed under the conditions indicated above, constitutes the greater part of the cementitious material of these compounds.

The higher the alumina content in any of the aluminates, the slower will be the reaction with water and consequently the slower will be the time of setting. This is shown in Table III, but not very clearly unless studied in connection with the relative amounts of the constituents shown in Table II. The former table shows that cement No. 3 has a slower setting time than cements Nos. 1 or 2, and also a lesser alumina content. The latter table, however, shows the presence of a large amount of silica and therefore the presence of a quantity of silicate which reduces the amount of alumina in the former cement and also retards the setting time. The two silicates present in these cements react very slowly with water, in fact the ternary compound 2 $CaO.Al_2O_3.SiO_2$ reacts so slowly that it will not form a cementing material, while the orthosilicate, 2 $CaO.SiO_2$, at the end of a year shows but little more than 5 per cent water of hydration but a very satisfactory strength. Also a comparison of cement No. 8 with cements Nos. 1 and 2, or cement No. 7 with Nos. 5 and 6 will confirm the statement that increasing alumina content gives a slower setting cement. This has been more strikingly shown in other work carried on with the pure compounds when it was found that the tricalcium aluminate—the aluminate lowest in alumina—always gives a flash set.

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[1] Rankin, "The Ternary System $CaO-Al_2O_3-SiO_2$," *American Journal of Science*, Vol. 39, January, 1915.

[2] Bates, "The Hydraulic Properties of the Calcium Aluminates," *Journal*, Am. Ceramic Society, Vol. 1, p. 679, October, 1918.

[3] The amount of water of hydration has never been very closely determined. Some water is lost at such low temperatures, that adhering water or moisture cannot be removed without removing some combined water.

With the exceptions of cements Nos. 2, 3 and 8, the burning temperatures used were either those generally used in burning Portland cement or a little lower. The temperatures used in these three exceptions were not much in excess of that infrequently used in making the latter cement and can be comparatively easily reached in a rotary kiln. One point in particular should be noted: it is impossible to produce an unsound cement unless a temperature far below that used in Portland cement practice were attempted. Slight underburning or burning at a temperature of 100° lower than that given would have produced an aluminate lower in alumina and free alumina.

Table V shows the strengths produced by the cements when tested in the form of a 6 by 12-in. cylinder as a $1:1\frac{1}{2}:4\frac{1}{2}$ gravel concrete. In order that some idea may be obtained in a comparative way of their deportment as a mortar, the compressive strengths of some 1:3 standard sand 2-in. cubes are given in Table IV. Previous work showed that, on account of the large amounts of colloidal material formed in the process of hardening, retrogression is likely to be shown by any specimens stored continuously in water or the damp closet. At certain periods, therefore, some of the specimens were removed from the water or damp closet and placed in the air of the laboratory until broken.

These two latter tables very clearly show the high 24-hour strengths. Special mention should surely be made of strengths of 2800 to 3100 lb. per sq. in. for a 1:6 concrete at the end of 24 hours. The strengths of some of the 1 : 3 mortars at the end of the same time is just as unusually high. The gain in strength with aging is also quite large, although maximum strength is reached at a comparatively early period. Consequently some very phenomenal strengths for either kind of a specimen are developed. A compressive strength of 8610 lb. per sq. in. at seven days for 1 : 3 mortar or 6010 lb. at the same period for 1 : 6 concrete are surely striking. While these results represent some of the maximum ones obtained, there are many other very exceptional high strengths shown in the tables, when these are compared with the results generally obtained with Portland cement.

An examination of the tables shows that the maximum strength for the water or damp closet stored specimens was attained at some period previous to one year. As stated before, the quick hardening is due to a great amount of hydrated material rapidly formed. This is also in the colloidal form and will, therefore, in the presence of excess water, take up in a comparatively short time such an excess of the latter that there is a reduction in strength. It will not take up enough from air of the usual humidity to materially affect the strength. It does, however, lose water to the latter to a certain extent. It is this latter loss of water with consequent drying out of the

TABLE IV.—COMPRESSIVE STRENGTH OF 1:3 STANDARD SAND MORTARS, FROM CALCIUM-ALUMINATE CEMENTS.

ALL VALUES IN POUNDS PER SQUARE INCH.

Tested at	24 Hours.	7 Days.	28 Days.	28 Days.	90 Days.	26 Weeks.		1 Year.
Stored in	Water.			C. S.	Water.	Water.	C. S.	Water.
Cement No.								
1	3570	5945	3765	6815	3945	5330	6015	3045
2	4260	4760	3945	7625	4735	4570	5290	4430
3	2240	4940	6475	8000	7180	7760	11 050	5315
4	4410	4880	5285	6400	4565	3470	3480	3200
5	1035	1400	1820	2875	2070	2900	3845	2410
6	1340	1260	1425	3130	1680	1895	4345	2310
7	2165	5140	3930	7085	5205	3605	6090	5225
8	2860	8610	7845	10 690	8260	6380	8045	8945

C. S. = Stored for one quarter of period in water and the remainder in the air of the laboratory.

TABLE V.—COMPRESSIVE STRENGTH OF 1:6 AND 1:12 GRAVEL CONCRETE, FROM CALCIUM-ALUMINATE CEMENTS.

ALL VALUES IN POUNDS PER SQUARE INCH.

Tested	24 Hours.		7 Days.		28 Days.		90 Days.		26 Weeks.		1 Year.			
Proportions[b]	1 : 6	1 : 12	1 : 6	1 : 12	1 : 6	1 : 12	1 : 6	1 : 12	1 : 6	1 : 12	1 : 6	1 : 6[a]	1 : 12	1 : 12[a]
Cement No.														
1	2825	....	3270	....	3310	....	4150	....	4180	....	3310	5590	....	....
2	3000	....	4150	....	4740	....	2480	....	1760	....	1760	2360	....	....
3	Soft	....	2175	....	3680	....	3900	....	4525	....	4135	5660	....	....
4	3145	880	3570	1005	3370	1000	2930	875	2565	800	2965	3280	860	1275
5	310	Soft	885	225	1250	365	1050	390	1270	550	1460	2110	570	870
6	840	275	765	275	990	305	1260	400	1515	470	1440	2035	470	810
7	1475	455	4135	1405	4625	1500	4640	1600	4450	1580	4650	5300	1350	1815
8	2930	890	6010	2270	7060	3415	7050	3980	7610	3910	6720	8220	3930	4445

[a] All specimens in these columns were stored for the first 4 months in the damp closet and for the remainder of the period in the air of the laboratory. All other specimens were stored in the damp closet for the entire period aged.

[b] Contained 3 per cent plaster.

colloid which causes the increase in strength of the water-air or damp closet-air storage over the storage in the water or damp closet alone.

It is interesting to note that in the case of the mortar specimens, cements Nos. 3, 5 and 6 developed the highest strengths by the combined method of storage at the end of the 26-week period, while the other cements developed their maximum strength by this method of storage at 28 days. Apparently, therefore, the latter were much quicker hardening than the former. Concrete specimens aged by the combined method were broken only at the one-year period. At this period by this method of storage maximum strength was developed by all the cements except Nos. 4 and 2. These latter developed maximum strength by damp closet storage at 7 and 28 days respectively. The continued storage of these two in the damp closet until removed to the air apparently caused such excessive hydration that subsequent drying out could not cause sufficient gain in strength to bring back the maximum strength shown at the earlier period. A shorter period of damp closet storage before the removal to the air would have been necessary in these two cases to have brought out higher maximum strengths. It should be remembered that the high early strengths are due entirely to rapid and more thorough hydration in the short intervals.

After the high results of the 1 : 6 concretes were obtained, it was thought desirable to make some leaner concretes. Consequently a 1 : 3 : 9 gravel concrete was made, using certain of the cements of which there was a sufficient amount available. Even such lean concretes developed surprising strengths in several cases. This is especially true of cement No. 8 which developed a strength of 3415 lb. per sq. in. at 28 days and 3980 lb. at 90 days, and a maximum strength, by the combined storage, of 4445 lb. per sq. in. at one year.

In conclusion it may be stated, therefore, that the aluminates of lime, even when they contain such amounts of impurities as 10 per cent silica and 3 per cent iron oxide, constitute a material which is a very valuable cementing medium when gaged with water. This particular value lies in the high early strengths which they develop. The greater the amount of the alumina present, as an aluminate of lime, the greater will be the early strength. Under certain conditions of curing there is a marked increase of strength with age, but this does not extend over a very long period of time. It also appears that if the concrete is subjected to an excess of water during curing there will be a decrease in strength. Such amounts of moisture as are usually present in the air do not materially affect the strength. It appears, therefore, that these cements might be of considerable value for certain special uses, where the principal requisite would be quick hardening.

DISCUSSION.

Mr. Thompson. MR. SANFORD E. THOMPSON.—I am rather surprised that Mr. Bates, in his paper, did not refer more distinctly to this variable quality of the magnesia cement. About every two or three years there is heralded the "invention" of a quick-hardening cement. Several years ago some one almost interested quite a large construction company in the east in a remarkable cement that he had discovered. On investigation, it proved to be simply one of these magnesium compounds which do not stand up under ordinary tests.

My experience in testing the Sorel cements has been that, whereas they do harden up and show remarkable strengths in short periods, they go to pieces and check up in a few months or a year and cannot be depended upon. Should not that have been mentioned more emphatically in the paper?

Mr. Bates. MR. P. H. BATES.—Perhaps so; but at the same time I do not think there is a steel passenger car in the country that has not Sorel cement floors, so while it may be erratic material it has a wide application and a wide use.

Mr. Lesley. MR. ROBERT W. LESLEY.—I think I have had experience with both varieties of cement discussed by Mr. Bates. I was interested some time ago in telling some friends of mine who went into the Sorel cement business and made beautiful vestibule slabs and floors, what difficulties were ahead of them. They were induced to go into the business in a large way and do exterior work, as well as the interior work in which they had been moderately successful. They built a fine building; the sills, lintels, columns and all were of Sorel cement. It looked well for a while, until a heavy rainstorm came; and the building dissolved—also the company. We investigated that and found out that what Mr. Thompson has stated was true; the material is not to be relied on in all classes of work and is not very trustworthy in many ways.

As to the Alca or alumina cement, I recall a paper read before one of the technical societies on the addition of alumina, from

Mr. Lesley. high alumina slags of the Pennsylvania Steel Co. made from Cuban ore, to lime to make the commercial product known as Alca Cement. Mr. Spackman took out a number of patents on that; he was very successful and made a very good exterior building material for plastering and also a plaster for interior work. However, that material, like the Sorel cement, was dependent on someone else's by-product. It is very interesting, but it does not operate. I might say, in connection with the Alca cement business, that it is still running on and has many customers.

Mr. Conwell. Mr. E. L. Conwell (*by letter*).—Mr. Bates' admirable paper is of more than ordinary interest to Henry S. Spackman Engineering Co., on account of our own work on calcium aluminates which commenced about 1902.

While we were mindful in 1908 of the value of slow-setting but quick-hardening aluminates for special purposes, no commercial application of the same occurred until the war showed the need of a cement for gun foundations that could be used in a day or so. In April, 1917, we submitted information on the utility of aluminate cements for the quick construction of foundations and other emergency structures to the United States Government, but so far as is known no use was ever made of the suggestion. The French Government recognized early in the war the necessity of a cement that would develop conventional 7-day strength in 24 hours, and for the last three years of war the La Farge works produced "Artillery Cement" which owed its quick-hardening properties to high calcium aluminate content. Plenty of bauxite is to be had in France, which permitted the manufacture of aluminates; while the Central Powers, having magnesite but little or no bauxite, turned to Sorel cement for purposes which demanded immediate development of notable strength.

The effect of alumina content on the setting time and rate of hardening was recognized by us in 1907 and 1908. The degree of burning also plays an important rôle. In our research work, it was found that high-lime aluminates were comparatively slow setting, if very hard burnt, and that those containing high alumina content were flash setting if underburnt. While Mr. Bates reports that sulfuric anhydride additions were found to

Mr. Conwell.

accelerate the set, we found in the case of all but the high-lime aluminates that it retarded the set. This method of regulating set was not entirely satisfactory, however, and we determined to try regulating the set of the high-lime aluminates by the addition of small quantities of low-lime aluminates. This was found to be effective. Following this, mixtures of aluminates of diverse composition in various proportions were tested. In most cases these mixtures showed extraordinary strength at 24 hours and at later periods were notably above the strength of Portland cement. Certain of our compositions were quite similar to those of Mr. Bates.

For example, one of our early low-lime aluminates mentioned in a patent, filed March 29, 1909, had the following composition:

Silica	2.12	per cent
Alumina	65.32	"
Iron oxide	12.16	"
Lime	20.94	"
Magnesia	0.44	"

This was made from bauxite and limestone, was hard burnt, and had an initial setting time of two hours, and final of four hours. It was sound toward steam and boiling water, and when tested as a 1:3 mortar, gave the following tensile strength:

24 hours	307	lb. per sq. in.
7 days	383	" "
28 days	465	" "
3 months	592	" "

A mixture of equal parts of this aluminate, and a higher lime aluminate having the composition:

Silica	2.76	per cent
Alumina	37.27	"
Iron oxide	6.47	"
Lime	47.12	"
Magnesia	0.46	"

was found to have the following properties:

SETTING TIME.

Initial	5 hr.
Final	5 hr. 30 min.

Mr. Conwell.

TENSILE STRENGTH, 1:3 MORTAR.

Water Exposure.			
24 hours	385 lb.	per sq.	in.
7 days	500	"	"
28 days	512	"	"
3 months	695	"	"
Air Exposure.			
7 days	370	"	"
28 days	580	"	"
3 months	775	"	"

It is believed that to Mr. Bates belongs the honor of being the first to reveal compression tests on aluminates made into concrete. For convenience, most of our work was conducted with tension tests, but we made compression tests in 1908 and in the same year made and used on a semi-commercial scale the low-lime aluminate previously mentioned, which is strikingly similar to composition No. 8 mentioned in Mr. Bates' paper. The properties of this low-lime aluminate were described fully in papers presented before various organizations in 1909 and 1910, and in several patent applications, and its value for constructing machine foundations which could be used in 24 hours was advocated to many people as an expedient to avoid factory shut-downs, when changing machinery. In November, 1908, we made 1000 lb. of this aluminate in an upright kiln at Wilmington, Del., and used it experimentally for many purposes for which Portland cement is used. It had all the properties that make Portland cement desirable, combined with slow setting and quick hardening, which it is felt were obtained by ourselves in a cement for the first time.

It is desired to express our cordial appreciation of Mr. Bates' work, the publication of which throws much light on why our aluminates of ten years ago possessed certain properties.

Mr. Bates.

Mr. BATES (*Author's closure by letter*).—Notwithstanding the rather unfavorable views of Mr. Thompson and Mr. Lesley in regard to Sorel cement, it remains a fact that this material has been in use for a great number of years and has given satisfactory results, and furthermore its use is increasing rapidly. Many of the members of this Society have for years been entering and leaving Atlantic City via the Pennsylvania Railroad. They

Mr. Bates. have possibly failed to note that the flooring in this station at Atlantic City is made of this cement. Its condition after this very severe usage is perfect.

Several years ago the Bureau of Standards inaugurated an investigation of the various materials used in stucco. In the course of this investigation they erected a building the exterior of which was divided into panels. These were covered with a great variety of stuccoes. Among the number was one made of Sorel cement. This stucco has not "dissolved," neither has it gone "to pieces and checked up in a few months or a year," though it has been exposed about four years.

The cements high in alumina discussed in the paper are in no way similar to "Alca," or any other high-alumina material made as a by-product. The cements in question were made from limestone and alumina. Neither were a by-product. They were made in a way differing in no wise from that used in manufacturing Portland cement. That cements of this character would have some commercial value is well brought out by Mr. Conwell's discussion which represents their satisfactory use during the last three years. Personally, I doubt very much whether they could be used where exposed to the continuous action of water, but on the other hand there are many places, such as reinforced concrete buildings, where cement is never subjected to the continuous action of water. The difficulty in the commercial use of these cements would not be in their deportment but in their original cost.

SOME THEORETICAL STUDIES ON PROPORTIONING CONCRETE BY THE METHOD OF SURFACE AREA OF AGGREGATES.

By R. B. Young.

SUMMARY.

This paper describes some theoretical studies on the surface area method of proportioning which were made preliminary to undertaking experimental proof of the applicability of this method to concrete.

It contains evidence to prove that the fineness modulus of an aggregate varies approximately as its surface area, although the former bears no mathematical relation to the latter.

In it is derived a formula for the quantity of water required to gage a mortar or concrete from which a graph giving the relation between the compressive strength and cement content of a mortar or concrete is obtained theoretically. This is shown to be identical in form with the curves already obtained experimentally by several investigators.

It shows further that if this formula for the water content of a mix is based on correct premises the cement content of a mortar or concrete must vary with the surface area of the aggregate used if a constant water-cement ratio and therefore a constant compressive strength is to be maintained.

It answers two criticisms of the method and shows:

1. That it is not necessary to obtain the actual surface area of a material if a value can be obtained which varies in accord with it;

2. That the present method of calculating surface area gives such a value;

3. That the fact that the cement is made up of minute particles which only make contact with the aggregate is no objection to the method since the number of particles of cement in contact with any particle of aggregate is a function of the area of the surface of that particle of aggregate.

SOME THEORETICAL STUDIES ON PROPORTIONING CONCRETE BY THE METHOD OF SURFACE AREA OF AGGREGATES.

By R. B. Young.

When the writer first seriously studied the paper on "Proportioning the Materials of Mortars and Concretes by Surface Area of Aggregates"[1] presented by L. N. Edwards before this Society at its last annual meeting, he was impressed with both its simplicity and its adaptability. It seemed to him to contain certain salient points found lacking to a large extent in any other method with which he was then acquainted and it was the lack of these points which had caused the greatest difficulty in the field. If this method could be applied to proportioning concrete it would provide:

1. A means of accurately estimating the strengths of concretes produced from any combination of cement and aggregate;

2. A means of maintaining a constant strength with the fluctuations in grading inevitable with natural materials, and a foundation upon which to build a simple and inexpensive system of laboratory and field tests for determining the relative concrete-making values of materials, and the proportions in which they must be combined to give desired results.

This method of proportioning possesses the further advantage that the underlying theory was so simple it could be explained to and would be appreciated by even the laborers on concrete work.

The lack of these important features is in a great measure accountable for the attitude of construction men towards any method of concrete proportioning other than by "rule-of-thumb." The field engineer is a man with a practical turn of mind who has to do mainly with men of a type impatient with involved methods and hampering restrictions. A method, to gain his respect, must give him an unequivocal answer to the question: "How much cement must I use under the conditions existing on this work to get the results which are required of me?" When a method is proposed which will not give him a direct answer to this he loses faith in it, which is quite natural when you appreciate his point of view. He is interested in ways of getting certain desired results and he expects your method, the tool with which he is expected to work, to do this or else he is a little contemptuous of it. If its theory and application is at all involved he is apt to become skeptical and to consider it only a tool to be used by experts and scientists. Any method of proportioning which does not take cognizance of this attitude will never gain his support, no matter how meritorious it may be, and without his unqualified support it is very difficult to get results.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 235 (1918).

Contemplation of the above conditions led naturally to the consideration of experimental proof of the applicability of the surface area method of proportioning concrete, but realizing the time and expense involved in such tests, if properly carried out, it was decided to make some further studies of this method before recommending any action along this line.

The work of D. A. Abrams[1] in his researches on concrete at the Lewis Institute in Chicago has established many important facts concerning concrete and it was felt that the surface area method to be worthy of consideration had to be in agreement with these facts. Consequently the first study undertaken was to connect the work of Abrams with that of Edwards. The results obtained from this study show the work of these two investigators to be in entire agreement, Abrams' work throwing much light on Edwards' results and vice versa.

The first step taken was to determine if any relationship existed between Abrams' fineness modulus and the surface area of a sand. This was done by calculating the fineness modulus and surface area of fifty representative sands, the mechanical analyses of which were assumed. The fineness modulus obtained in this case was not exactly that of Abrams', since other sizes of sieves were in use, but the openings of these bore the same relationship to one another as did his and it was derived in a similar manner. The analyses chosen gave a range of values exceeding 400 per cent. When these were plotted in the form of a graph with surface area as ordinate and fineness modulus as abscissa, as in Fig. 1, it was found that the relation between these two was approximately that of a straight line. This was considered a very important point, for might it not be possible that the success which had been obtained with the fineness modulus in estimating the strength of and in proportioning concrete mixtures was due to this? It seems extremely likely, for so far as is known to the writer no explanation of the reason for the success of the fineness modulus has ever been advanced accounting satisfactorily for its remarkable properties.

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[1] *Proceedings*, Am. Conc. Inst., Vol. XIV, p. 22 (1918).

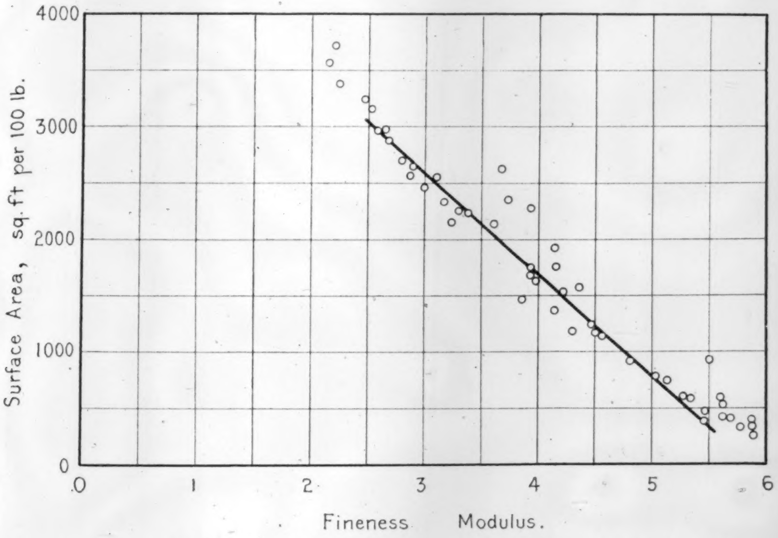

FIG. 1.—Relation between Fineness Modulus and Surface Area of Aggregates.

As a proof that the fineness modulus was not the same as the surface area of a material, but only a happy approximation of it, a formula for each was worked out as follows:

Let us consider a set of six sieves, No. 1, 2, 3, 4, 5 and 6, the diameters of the openings of which decrease by one-half with each succeeding sieve in the set. It was found by actual experiment with a set of sieves having this ratio that the surface area per gram of material passing a certain sieve and retained on the next finer was double that retained on that sieve but passing the next coarser. If, therefore, we take x as being the surface area per gram of the material lying between Nos. 1 and 2, $2x$ will be the surface area per gram of that between Nos. 2 and 3, $4x$ between that of Nos. 3 and 4, and so on. Let a, b, c, d and e be the percentages remaining between the different sieves as in Table I, then the fineness modulus is:

$$\frac{5a+4b+3c+2d+e}{100},$$

and the surface area per unit volume is

$$16ex+8dx+4cx+2bx+a$$

or

$$x\,(16e+8d+4c+2b+a).$$

In other words, the two have no mathematical relation, one to the other. Fig. 1 would lead one to suspect this, as but few of the points fall exactly on the line drawn.

TABLE I.

Sieve No., Pass-Retained.	Mechanical Analysis, per cent remaining between sieves.	Per cent Retained on Each Sieve.	Surface Area per Unit of Volume.
1–2	a	a	ax
2–3	b	$a+b$	$2bx$
3–4	c	$a+b+c$	$4cx$
4–5	d	$a+b+c+d$	$8dx$
5–6	e	$a+b+c+d+e$	$16ex$
Total	100		

Abrams has also shown that the strength of a concrete or mortar mixture depends upon the ratio of the volume of water to the volume of cement in that mixture. Strength is, therefore, a function of the water content of the mix. Upon what does the quantity of water depend, assuming that we use only sufficient to give a workable consistency? On consideration, we find that it is upon the quantity required to reduce the cement to a paste plus the quantity necessary to wet the surfaces of the particles of aggregate. The quantity required to wet the cement depends entirely upon the quantity of cement used, while the quantity required to wet the aggregate depends upon the total surface area of the particles making up the aggregate and the latter is, in turn, dependent upon the sizes of the particles and the number of each size present in any given aggregate; or in other words, upon its grading or mechanical analysis. If we assume the cement content and consistency to be the same, the conclusion then follows that the concrete which is made from the aggregate having the least surface area will require the least water in excess of that required to wet the cement and will, consequently, be the strongest.

Strength depends upon the "water-cement" ratio and yet increases in strength may be obtained by increasing the cement content of a concrete. How can this be explained? An additional quantity of cement in a concrete requires an additional quantity of water only sufficient to properly moisten the additional cement used, and therefore the total quantity of water does not increase in the same ratio as the total quantity of cement: that is to say, the water-cement ratio decreases with a consequent increase in the strength of the concrete.

With these facts in mind we can derive a formula for the amount of water required to give a desired consistency:

Let W = the total amount of water required in cubic feet,
C = the amount of cement required in cubic feet,
x = the "water factor" of the cement or the volume of water in cubic feet required to reduce one cubic foot of cement to a paste,
a = the surface area of the aggregate used in square feet divided by 100,
n = the "water factor" of the aggregate or the volume of water in cubic feet required to wet each 100 sq. ft. of its surface area.

Then

$$W = xC + na \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This may be simplified if na is taken to equal L, L being, therefore, the water required to wet the aggregate in any given case. The equation then becomes

$$W = xC + L \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which is the most convenient form for general use.

From Abrams' experiments we have found that the relation of compressive strength to the water and cement used given by the equation

$$S = \frac{A}{B^R}$$ [1]

in which S = compressive strength in pounds per square inch, A and B constants depending on age, materials and other conditions affecting the cement, and $R = W/C$, or "water-cement" ratio.

Substituting for W in Eq. 2 we have

$$R = \frac{xC+L}{C} = x + \frac{L}{C} \qquad (3)$$

which gives by transposition

$$L = C\ (R - x) \qquad (4)$$

and

$$C = \frac{L}{R-x} \qquad (5)$$

By means of these formulas we are able to deduce several interesting conclusions which, if the premises are sound on which the formulas are based, should be capable of experimental proof. With the consistency or plasticity of a mix maintained constant let us first determine the relationship between the compressive strength of a concrete and its cement content. In this case, since the plasticity is maintained uniform the quantity of water required to wet the surfaces remains the same and the only change in the quantity of water occurs in that part necessary to properly moisten the cement. For simplicity, let us consider a numerical example in which the following conditions govern:

The amount of water required to wet the cement = 22 per cent by weight; the surface area of combined aggregate is 2400 sq. ft.; the amount of water required to wet the aggregate is 0.75 lb. per 100 sq. ft. of surface area of aggregate; cement proportioned on the basis of 1, 2, 3, 4 and 5 lb. per 100 sq. ft. of surface area of aggregate; and

$$S = \frac{14000}{7^R}.$$ [2]

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[1] *Proceedings*, Am. Conc. Inst., Vol. XIV, p. 22 (1918).

[2] *Engineering News-Record*, May 2, 1918, p. 872.

Our constants then become

$$a=24.00,\ n=0.75$$

and therefore

$$L=\frac{0.75\times 24}{62.5}=0.288 \text{ cu. ft.}$$

$$x=\frac{\text{Weight of 1 cu. ft. cement}\times\text{water required to wet cement}}{\text{Weight of 1 cu. ft. of water}}$$

$$=\frac{87.5\times 0.22}{62.5}=0.308 \text{ cu. ft.}^{1}$$

C for the first case, in which the cement is proportioned 1 lb. per 100 sq. ft. of surface area, is equal to

$$\frac{1\times 24}{87.5}=0.274$$

and the water-cement ratio becomes

$$R=0.308+\frac{0.288}{0.274}=1.358 \text{ (from Eq. 3)}$$

and

$$S=\frac{14000}{7^{1.358}}=1074 \text{ lb. per sq. in.}$$

Similarly R and S can be calculated for each of the other ratios of cement to surface area given. The result of such calculation is given in Table II.

TABLE II.

Cement, lb. per 100 sq. ft. surface area.	Cement, C, cu. ft.	Water-Cement Ratio, R.	Compressive Strength, S, lb. per sq. in.
1	0.274	1.358	1074
2	0.548	0.833	2770
3	0.822	0.658	3900
4	1.096	0.571	4605
5	1.370	0.518	5100

---

[1] The standard Canadian bag of cement weighs 87.5 lb., and is assumed in these calculations to contain 1 cu. ft. of cement.

Plotting the values of *S* and *R* we obtain the curve given in Fig. 2. This relation is not that reported by Edwards in his paper last year, but when Edwards' charts were examined after Fig. 2 was obtained, it was found that he had been misled into believing this a straight-line relation by the limited range covered by his tests and that actually four of the six sets of points shown on his charts could be better expressed by a curve similar to that of Fig. 2 than by the straight lines actually shown in his paper. Figs. 3 and 4 show these. The results of other investigators were likewise consulted and the same relation was found to hold. Among these were the results obtained by

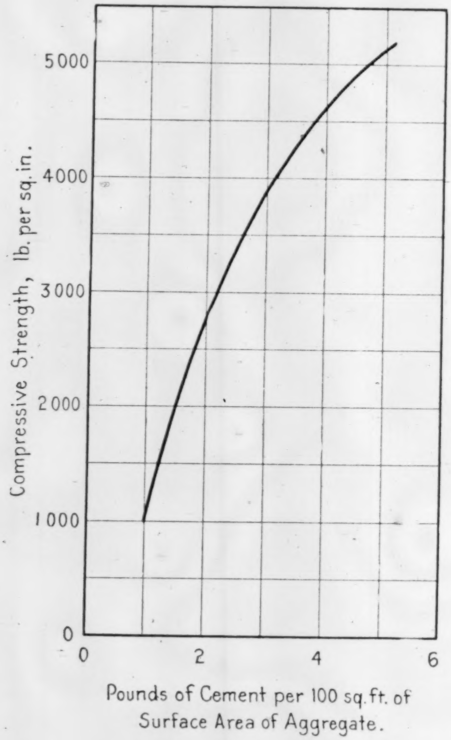

FIG. 2.—Relation between Compressive Strength and Cement Content.

Messrs. Fuller and Thompson,[1] some of which are shown in Fig. 5. Fig 6 shows results recently obtained in the Laboratories of the Hydro-Electric Power Commission of Ontario from a test covering the same range of proportions assumed in the calculated set of Table II.

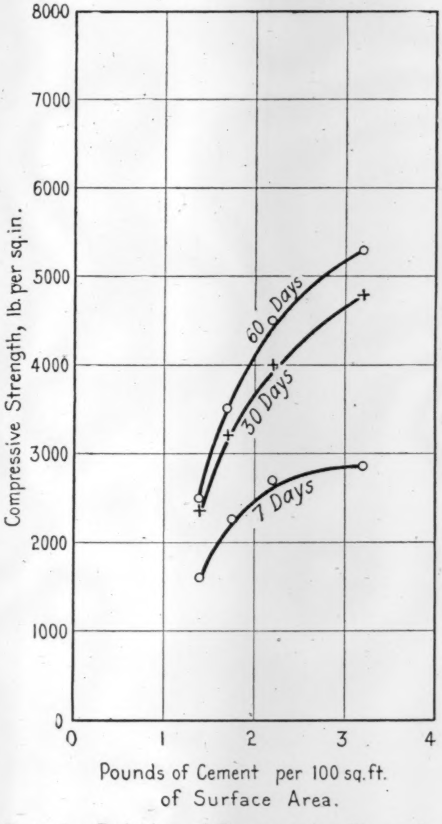

FIG. 3.—Relation of Compressive Strength of Mortars to Volume of Cement in Mix (Edwards, 1918).

In the case just discussed the grading of the aggregate and the consistency of the mix were constant, and the relationship between the compressive strength of a concrete and its cement content was found. If instead, the aggregate varied but the consistency and compressive strength were to be maintained constant, how should the cement content be proportioned to bring this about? For each strength there is a constant ratio of volume of water to volume of cement, hence the first requisite for constant strength is that this ratio be maintained constant. Secondly, with a change in grading there is a change in surface area and a corresponding change in the amount of water needed to wet the aggregate. Let us now consider the formula $C = L/R - x$. For any given strength R is constant and as long as

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[1] *Transactions*, Am. Soc. C. E., Vol. LIX, p. 67 (1907)

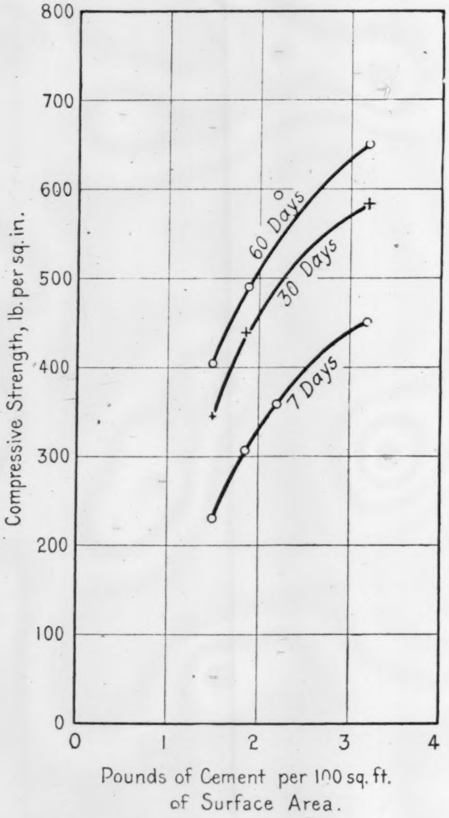

FIG. 4.—Relation of Tensile Strength of Mortars to Volume of Cement in Mix (Edwards, 1918).

the nature of the cement does not change x is constant. Therefore C varies directly with L, but since $L=na$ where n is a constant for any particular aggregate, L varies directly with a and therefore C also varies directly with a, or with the surface area of a unit volume of aggregate. Hence to maintain a constant strength and therefore a constant R, it is necessary to proportion the cement C on the basis of the surface area of the aggregate.

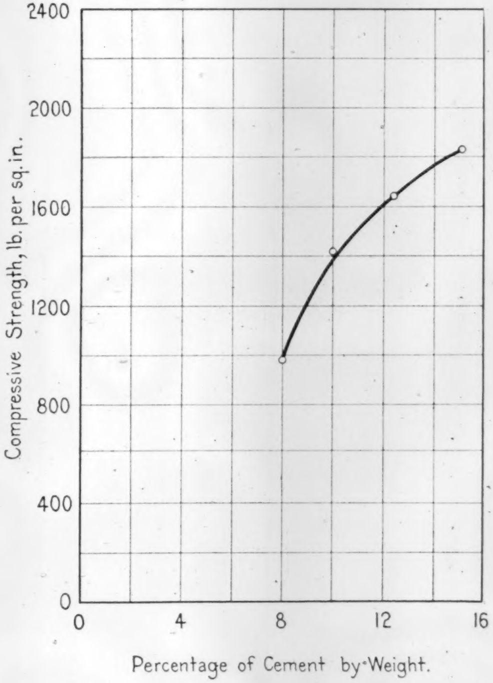

FIG. 5.—Relation of Compressive Strength of Concrete to Weight of Cement in Mix (Fuller and Thompson).

Table III shows in detail a number of aggregates having different mechanical analyses with their corresponding surface areas. These are shown proportioned to maintain a constant water-cement ratio R of 0.728, and the quantity of cement is given which is required to do this. The relation of volume or weight of cement to each 100 sq. ft. of surface area of the aggregate used is constant, as is shown in the last column of Table III.

Some criticism of the surface area method of proportioning has been offered because the value of the surface area obtained by Edwards' calculations was not the true surface area of the material. It was held that the aggregate particles are neither true spheres nor have they smooth surfaces, and since it is thus impossible to obtain their actual surface areas, the value for the surface area obtained is of no use. This was given consideration and after some experimental studies upon the uniformity of sand particles, the conclusion was reached that it is not essential that we know the exact surface area, for if we can determine a value for each case which has a constant relation to the actual surface area, the amounts of cement used in proportioning can be stated in terms of this value equally as well as in terms of the actual surface area. It seems reasonable to assume that the

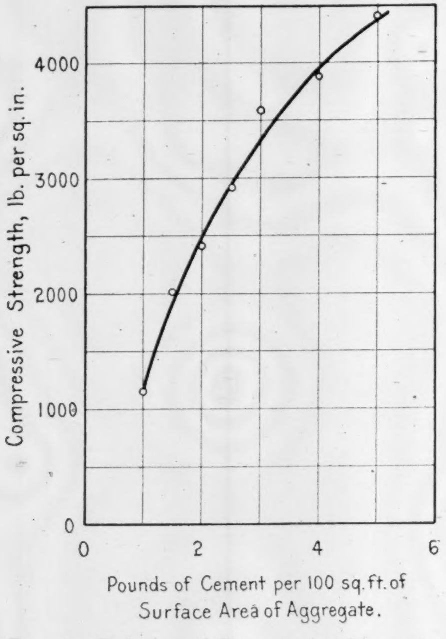

FIG. 6.—Relation of Compressive Strength of Concrete to Volume of Cement in Mix (Hydro-Electric Power Commission of Canada).

actual surface area in a cubic foot of particles of any particular size coming from a certain source is the same as another cubic foot of similar sized particles from the same source; it being very probable that there would be equal numbers of each of the many possible shapes of particles present in both cases, and the studies referred to herein have confirmed this assumption.

Another source of criticism has been the fact that the cement is itself made up of minute particles which do not form a continuous unbroken covering for the aggregate but, like the aggregate, simply make contact with these particles and with one another. Consideration of this point lead to the conclusion that with a uniform distribution of cement the number of cement particles in contact with any particle of aggregate is a function of the area of its surface, and hence this criticism offers no serious objection to the method.

TABLE III.

Surface Area of Aggregate, sq. ft.	Cement, C, cu. ft.	Cement, Total Weight, lb.	Cement, lb. per 100 sq. ft. surface area.
1600	0.457	40	2.5
2000	0.571	50	2.5
2400	0.686	60	2.5
2800	0.800	70	2.5
3200	0.914	80	2.5

The studies described above appear to offer conclusive evidence that the surface area method of proportioning is correct in principle. However, it was considered essential that its application to concrete be studied experimentally, and this work is now under way in the Laboratories of the Hydro-Electric Power Commission of Ontario, under the direction of the writer. It is not possible to give any account of these experiments at the present time, except to say that the results so far obtained bear out these theoretical deductions fully and, although the experiments are not yet completed, the results have been so encouraging that the method is being tried out in a practical way on a considerable scale upon several of the construction jobs of the Commission.

(For Discussion of this paper, see page 476.)

PROPORTIONING OF PIT-RUN GRAVEL FOR CONCRETE.

By R. W. Crum.

SUMMARY.

This paper has to do specifically with determining the amount of cement to use with pit-run gravel to make various classes of concrete. Although screened and remixed aggregates are preferable to pit-run material, still in many localities large amounts of pit-run gravel are used. The object of the investigation reported in this paper is to establish engineering methods for the proper use of such aggregate. In view of the character of very much of the work upon which pit-run gravel is used, the method of proportioning should depend upon a minimum of testing. The tests required are easily made in the field and do not require expensive apparatus. This method of proportioning depends upon the loose weight per cubic foot of the gravel and upon the percentage of material in the gravel which will pass a No. 4 sieve.

A brief comparison is included with the "Fineness Modulus" and "Surface Area" methods of proportioning. The proportions obtained by the method described herein appear to fall between those obtained by the two methods mentioned above.

PROPORTIONING OF PIT-RUN GRAVEL FOR CONCRETE.

By R. W. Crum.

The factors upon which the strength of concrete must depend are (1) the density of the concrete, and (2) the extent to which the particles are cemented together. The latter factor depends upon the amount of cement in a given volume, and upon the total surface area of the particles.

Inasmuch as numerous authorities are agreed that the density of the mixture is partly and the surface area wholly dependent upon the grading of the aggregate, and that the density also depends upon the consistency, or amount of water in the mixture, the writer has formulated for his own use the following rule for proportioning concrete mixtures:

> Use the best graded aggregate available, enough cement to make concrete of the class desired, and mix with the least amount of water which will yield a workable mixture for the conditions under which the concrete is to be placed.

The material to be considered in this paper is pit-run gravel, to be used without change as it comes from the pit. The problem is to establish some relation between grading and the amount of cement such that, for mixtures of the same plastic consistency, concretes of equivalent strength could be designed.

To establish such a workable relation, it is necessary to express the grading of the gravel by numerical functions. Other experimenters, notably Abrams and Edwards, have done so, and their work could be used as a basis for proportioning pit-run materials. However, both Abrams' "Fineness Modulus" and Edwards' "Surface Area" method require the making of a complete sieve analysis of the material. The method herein described requires the separation of a sample into only two sizes and a simple determination of the weight per cubic foot of the loose gravel.

The principal conclusion resulting from the investigation carried out is that the grading of pit-run gravel may be measured by the ratio of fine aggregate to total aggregate (that is, percentage of fine aggregate in total) and by the weight per cubic foot of the material, measured loose. For purposes of commercial convenience the dividing line between fine and coarse aggregate is taken on the common No. 4 sieve. In the following discussion, fine aggregate as defined above will be called "sand," and coarse aggregate "pebbles."

Two assumptions have often been made by users in proportioning the cement to pit-run gravels:

1. That the ratio of cement to total aggregate should be a constant.

TABLE I.—RATIO OF CEMENT TO TOTAL AGGREGATE CONSTANT.

Per cent of "Sand" in Aggregate, by Weight.	Proportions (1:5).	Density.	Water, per cent of dry materials.	Compressive Strength, lb. per sq. in.
42..................	$1:2:3$	0.789	9.33	1600
55..................	$1:2\frac{3}{4}:2\frac{1}{4}$	0.770	10.65	1200
75..................	$1:3\frac{3}{4}:1\frac{1}{4}$	0.737	12.6	920
95..................	$1:4\frac{3}{4}:\ \frac{1}{4}$	0.673	15.30	480

2. That the ratio of cement to the sand portion of the aggregate should be a constant.

The former is wrong and on the unsafe side. The latter is also wrong but is on the side of safety.

RATIO OF CEMENT TO TOTAL AGGREGATE CONSTANT.

Table I is typical of the strength of concretes made under the assumption that the ratio of cement to total aggregate should be kept constant. Further demonstration of the fallacy of this assumption is not necessary.

RATIO OF CEMENT TO SAND CONSTANT.

The assumption that the ratio of cement to percentage of sand in the gravel should be a constant was investigated in twenty-four series of tests. Materials from several localities and two classes of concrete were used. Table II gives physical characteristics of the aggregates used in the investigations described herein.

TABLE II.—PHYSICAL CHARACTERISTICS OF AGGREGATES USED.

Sand No.	Pebbles No.	Percentage of Voids, Loose.	Loose Weight, lb. per cu. ft.	Percentage of Silt.	Specific Gravity.	Sieve Analysis: Per cent Passing Sieve No.								
						......	......	......	4	8	14	28	48	100
						Size of Opening, in.								
						1.5	0.75	0.371	0.185	0.093	0.046	0.023	0.0116	0.0058
1	....	39.8	99.9	4.0	......	......	......	......	......	100.0	67.5	25.5	6.5	1.5
2	....	39.3	100.7	2.0	......	......	......	......	......	100.0	83.5	57.0	18.5	4.5
3	....	42.2	95.9	9.0	......	......	......	......	......	100.0	72.5	37.0	12.0	7.0
4	....	37.9	103.0	2.0	......	......	......	......	......	100.0	82.0	49.5	10.0	3.8
5	....	40.5	98.4	4.0	......	......	......	......	100.0	82.0	58.0	23.6	5.8	1.5
6	....	......	......	1.3	......	......	......	......	100.0	87.0	69.5	45.2	16.0	2.0
7	....	45.0	91.3	7.5	......	......	......	......	100.0	79.8	55.3	28.2	10.0	3.8
8	....	39.7	99.8	0.8	......	......	......	......	100.0	85.2	66.5	39.4	6.2	0.3
11	....	41.2	98.8	2.0	2.68	......	......	......	......	100.0	87.6	43.2	11.1	1.3
12	....	41.3	101.1	1.8	2.75	......	......	......	100.0	96.4	60.1	32.9	18.2	3.8
13	....	42.0	99.1	1.8	2.73	......	......	......	......	100.0	76.6	39.3	9.7	1.8
15	....	41.2	98.7	2.0	2.69	......	......	......	100.0	85.2	59.7	31.6	8.6	1.2
16	....	39.3	104.4	1.6	2.75	......	......	100.0	92.8	61.5	35.2	17.9	9.7	2.1
17	....	42.3	98.5	1.5	2.72	......	......	100.0	98.0	83.9	61.3	30.6	7.4	1.6
20	....	40.0	100.0	2.0	2.68	......	......	100.0	99.1	87.7	63.7	33.7	9.1	2.1
21	....	37.7	103.6	......	2.66	......	......	100.0	99.4	87.3	59.8	31.5	10.2	2.1
....	9	37.5	103.7	0.0	......	100.0	89.7	52.8	29.6	1.9	......	......	......	......
....	10	41.6	98.1	0.0	......	100.0	84.5	24.2	3.7	0.8	......	......	......	......
....	18	42.4	102.3	0.0	2.81	100.0	86.9	49.2	27.9	8.4	......	......	......	......
....	19	42.4	100.0	0.0	2.82	100.0	74.8	31.7	10.3	......	......	......	......	......
....	22	42.2	101.0	1.5	2.80	......	100.0	82.5	31.5	1.6	......	......	......	......
....	23	37.4	103.5	1.0	2.65	100.0	64.9	52.5	12.7	1.1	......	......	......	......

Each series comprised tests of gravels containing respectively 42, 55, 75, and 95 per cent, by weight, of sand. The mixtures were made arbitrarily by combining sand and pebbles in the right amounts. The same sand and pebbles were used in each mixture in a series. Each series included tests of forty

TABLE III.—VARIATION IN COMPRESSIVE STRENGTH OF CONCRETE WITH THE PERCENTAGE OF SAND IN THE GRAVEL, WHEN THE RATIO OF CEMENT TO THE SAND PORTION OF THE GRAVEL IS KEPT CONSTANT.

CEMENT TO SAND=1:2 BY WEIGHT.

CLASS I—SAND PASSING SIEVE NO. 4—PEBBLES RETAINED ON SIEVE NO. 4 AND PASSING 1½ IN. SIEVE.

Series No.	Sand No.	Proportions							Weight, lb. per cu. ft		Absolute Volume: Parts of Unit Volume in Green Concrete.				Percentage Water in Mix, by Weight.	Compressive Strength, lb. per sq. in.	
		Weight.		Loose Volume.			Absolute Volume.										
		Cement to Aggregate.	Sand to Pebbles.	Cement to Aggregate.	Sand to Pebbles.	Computed for Equivalent Strength.	As Used.	Computed for Equivalent Strength.	Aggregate.	Green Concrete.	Cement (*c*).	Sand (*s*).	Pebbles (*p*).	$c+s+p=$ Density.		Age, 7 Days.	Age, 28 Days.
5	5	1:4.75	42:58	1:3.9	48:66	1:4.05	1:5.5	1:5.5	112.0	147.6	0.121	0.284	0.379	0.784	10.9	1235	1854
		1:3.66	55:45	1:3.2	62:51	1:4.1	1:4.3	1:5.5	110.2	149.0	0.148	0.346	0.292	0.786	11.2	1438	2275
		1:2.66	75:25	1:2.3	82:27	1:3.35	1:3.1	1:4.35	107.1	147.2	0.182	0.426	0.142	0.750	13.9	1637	2826
		1:2.10	95:5	1:2	97:5.1	1:3.2	1:2.5	1:3.9	100.1	146.1	0.209	0.493	0.030	0.732	14.8	2244	3532
6	6	1:4.75	42:58	1:3.8	48:68	1:3.9	1:5.4	1:5.4	114.8	146.1	0.122	0.279	0.383	0.784	9.8	1872	3360
		1:3.66	55:45	1:3.1	62:52	1:3.7	1:4.4	1:5.1	112.35	146.1	0.144	0.340	0.291	0.775	10.4	1792	3296
		1:2.66	75:25	1:2.3	80:27	1:2.7	1:3.1	1:3.6	107.1	141:2	0.175	0.408	0.137	0.720	13.2	2120	3452
		1:2.10	95:5	1:2	96:5.2	1:2.7	1:2.5	1:3.35	101.1	141.8	0.206	0.482	0.024	0.712	14.5	2360	3864
7	7	1:4.75	42:58	1:3.9	51:66	1:4.15	1:5.6	1:5.6	111.3	146.1	0.116	0.272	0.382	0.770	11.85	1150	2340
		1:3.66	55:45	1:3.2	65:49	1:4.05	1:4.25	1:5.3	107.8	145.6	0.145	0.339	0.276	0.760	12.1	1423	2872
		1:2.66	75:25	1:2.4	84:26	1:3.3	1:3.1	1:4.1	102.3	143.0	0.175	0.410	0.136	0.721	15.0	1550	3245
		1:2.10	95:5	1:2.1	98:4.6	1:3.35	1:2.5	1:3.8	94.0	142.0	0.204	0.480	0.024	0.708	15.3	2045	3680

specimens. Five specimens were broken for each test of a mixture. Specimens from all series were tested at 28 days old; specimens from some series were tested at 7 days and from others at 6 months. Specimens were 8 by 16-in. or 6 by 12-in. cylinders stored in water.

In some of the series the No. 8 sieve was taken as the dividing line between sand and pebbles. The general result was very similar to that obtained with the No. 4 sieve.

In Table III are given typical results of these tests for three series, showing the variation in strength of concrete with the percentage of sand in the gravel, when the ratio of cement to sand is kept constant. The strength increases with the percentage of sand in every mixture in the table, save one, and the results are typical of all series.

Obviously, neither the ratio of cement to total aggregate, nor the ratio of cement to the sand portion, should be a constant, but for equivalent mixtures the ratio of cement to total aggregate should increase in some relation to the percentage of sand in the gravel. That this is a straight line relation is demonstrated as follows:

THEORY FOR MAKING CONCRETES OF EQUIVALENT STRENGTH, USING GRAVELS OF VARYING SAND CONTENT—THE "SAND" METHOD.

This theory depends upon the assumption that there is a direct relation between the strength of concrete and the ratio

$$\frac{c}{1-(c+s+p)}=\frac{c}{1-d},$$

in which c = absolute volume of cement, s = absolute volume of sand particles, and p = absolute volume of pebbles in a unit volume of freshly made concrete; d = coefficient of density = absolute volume of solid material in a unit volume of freshly made concrete = $c+s+p$; and $1-d$ = volume of air and water voids.

By absolute volume of a granular material is meant the actual sum of the volumes of all of the particles; it is expressed as the fractional part of the total space occupied by the material.

The quantities are computed as shown in Taylor & Thompson's "Treatise on Concrete."

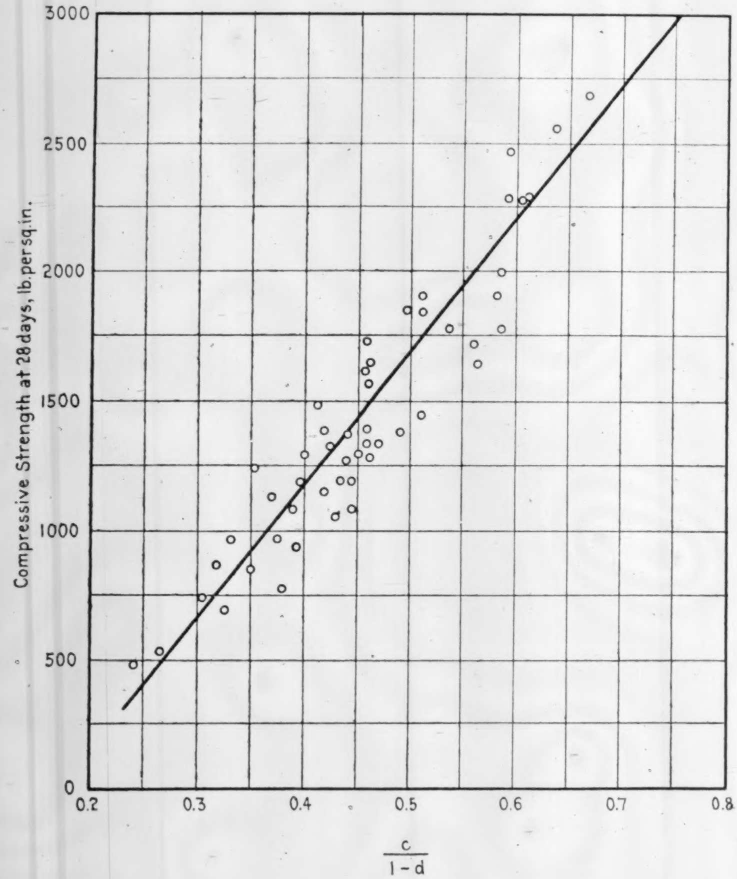

FIG. 1.—Relation between Compressive Strength of Concrete and the Ratio $\frac{c}{1\text{-}d}$; c = Absolute Volume of Cement and $(1\text{-}d)$ = Volume of Air and Water Voids in a Unit Volume.

Fig. 1 demonstrates the truth of the assumption that, other things being equal, the strength varies with $\frac{c}{1-d}$. The tests grouped on this diagram are comparable by reason of being made from the same cement, similar materials, and subjected to the same conditions as to making, molding, and curing. Each point is derived from the average of tests of five specimens. Diagrams of other groups of tests comparable among themselves give similar results. A similar diagram published in the last (1918) edition of Johnson's "Materials of Construction," computed from data published in U. S. Bureau of Standards Technologic Paper No. 58, corroborates this assumption.

In order to compute proportions for equivalent strength, it is necessary to assume for each class of concrete that some mixture is satisfactory. For the three classes of concrete considered in this paper, the following mixtures were taken as the basis:

Class I—Proportion 1:4½, gravel containing 42 per cent sand.
Class II—Proportion 1:5½, gravel containing 42 per cent sand.
Class III—Proportion 1:7, gravel containing 42 per cent sand.

Taking each series of tests by itself, the probable proportions to use with the different percentages of sand in the aggregate, to yield concrete equivalent to the one having 42 per cent of sand in the aggregate, were derived as follows:

DATA CONCERNING PROPORTIONS FROM TYPICAL SERIES (NO. 30).

Per cent of Sand in Aggregate, by Weight.	c	s	p	d	$\frac{c}{1-d}$
33	0.096	0.227	0.440	0.763	......
42	0.105	0.286	0.378	0.769	0.455
55	0.122	0.361	0.282	0.765	......
75	0.132	0.456	0.145	0.733	......
95	0.167	0.525	0.026	0.718	......

To arrange the proportions for equivalent strength it is necessary to so change the relation between the absolute volumes of cement and aggregate that the ratio $\frac{c}{1-d}$ will in each case become equal to 0.455. The adjustment can be made by increasing or decreasing c and decreasing or increasing $s+p$, so that d will be unchanged, thus:

Let c', s' and p' be the new values required for c, s and p, respectively. As explained above, these values are the percentages of absolute volumes of the materials in a unit volume of freshly made concrete.

$$\frac{c'}{1-d} = \frac{c'}{1-(c'+s'+p')} = 0.455$$

Therefore, to convert the mixture containing 33 per cent of sand:

$$\frac{c'}{1-0.763} = 0.455$$

$$c' = 0.108$$

$$d = c'+s'+p'$$

$$0.763 = 0.108 + (s'+p')$$

$$(s'+p') = 0.655$$

Accordingly the ratio of absolute volume of cement to absolute volume of total aggregate, required to make a proportion using the 33-per-cent sand mixture equivalent to the 42-per-cent sand mixture is

108 : 655, or 1 : 6.7

New proportions for the 55, 75, and 95-per-cent mixtures were computed in the same way.

This theory is approximate, not rigorous, for when the concrete is actually made, the density d will be affected a small amount. The result obtained, however, is within the probable range of accuracy in making the concrete.

The proportions thus derived are by absolute volumes. To make these proportions usable it is necessary to convert them to a loose volume basis, which requires the weight per cubic foot of cement and loose aggregate. Assuming cement to weigh 94 lb. per cu. ft., its specific gravity $= 3.14$, and that of the aggregate $= 2.68$, absolute volume proportion of aggregate (cement $= 1$) may be changed to loose volume proportion by the following equation:

$$\text{Aggregate (loose)} = \frac{\text{Aggregate (absolute)} \times 80}{\text{Weight per cu. ft. of Aggregate (loose)}}$$

In this way the absolute proportions and loose volume proportions of materials to yield concrete equivalent in strength

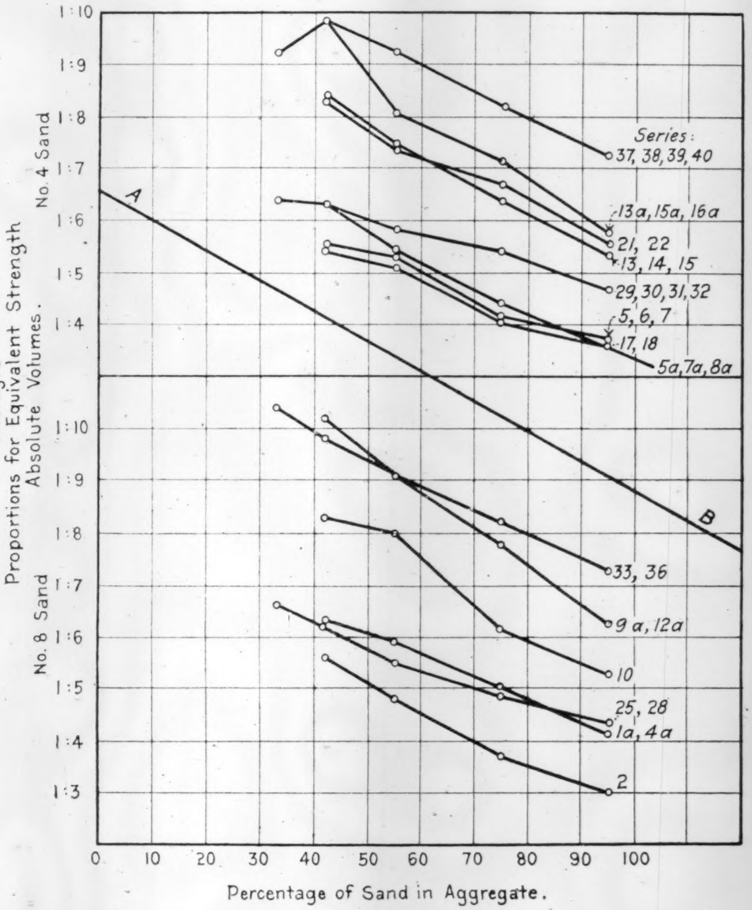

FIG. 2.—Relation between Percentage of Sand in Gravel, and Theoretical Proportions by Absolute Volume, Necessary to Yield Concrete Equivalent to a Given Base Mixture.

to the one in each series whose aggregate contained 42 per cent of sand, was determined for aggregates containing 33, 55, 75, and 95 per cent of sand.

In Fig. 2 the relation between the proportions for equivalent strength by absolute volume, and percentage of sand in aggregate, is shown for all of the specimens tested. Each line is the average of results from 3 or 4 different sands, and therefore represents the conclusion drawn from 3 or 4 series of tests. Each point is the average of from 75 to 100 individual specimens.

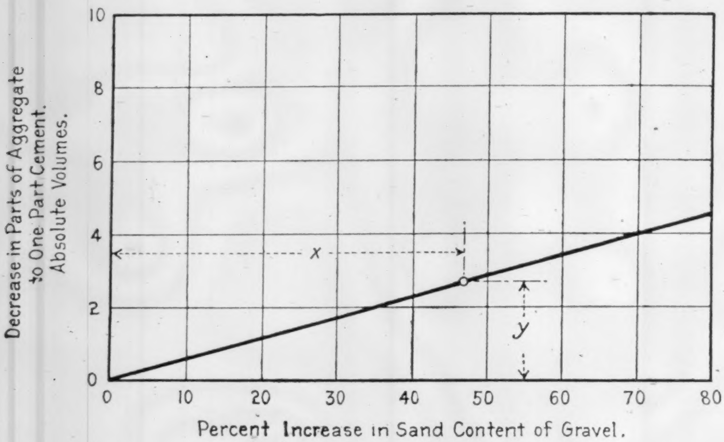

FIG. 3.—To determine the amount of cement to use with a given pit-run gravel to yield a concrete equivalent to a given mixture of sand and gravel:

1. Reduce the proportion of the standard mix to the basis of absolute volume.
2. Determine from curve decrease in parts of aggregate correspondingto increase in percentage of sand in aggregate.
3. Change the absolute volume proportions thus found to the loose volume basis.

Formula for computing Item 2.

$$\tan \alpha = \frac{3.6}{62} = 0.058 \text{ (See } AB\text{, Fig. 2)}$$

$$y = x \tan \alpha = 0.058\, x$$

The conclusion drawn from a study of this diagram is this: The relation between proportions by absolute volumes to give equivalent strength, and sand content of the aggregate, varies uniformly and at approximately the same rate for all degrees of quality of concrete. The line *AB* in the diagram is established to indicate this rate of variation as an average.

To make use of this diagram to determine the proportions to use with a given material having a certain sand content, it is necessary first to assume an aggregate and proportion known to be satisfactory. Locate the point representing this known condition and draw a line through it parallel to AB. Then pick from this line of proportions the proportion corresponding to the given aggregate.

To make a single line diagram of general application, the line AB (Fig. 2) is plotted on Fig. 3, using for ordinates the decrease in parts of aggregate, and for abscissas the increase in percentage of sand in the aggregate. This diagram can be used for determining proportions in a case when the proper data are at hand, or for writing a table of proportions for equivalent mixtures of cement and pit-run gravels in general. Such a table could not be exact for all materials, but it would give a very reasonable set of proportions to use with Iowa gravels.

Example.

Assume that an aggregate containing 42 per cent of sand, and weighing 112 lb. per cu. ft., makes a satisfactory concrete in the proportion 1:4½ loose volume. What proportion should be used with a similar gravel containing 75 per cent of sand and weighing 107.1 lb. per cu. ft.?

Change the proportion 1:4½ to a proportion by absolute volume, thus:

$$\frac{4.5\times 112}{80}=6.3 \qquad \text{Proportion (absolute)}=1:6.3$$

The increase in percentage of sand is 33. From Fig. 3 the corresponding decrease in parts of aggregate is 1.9. $6.3-1.9=4.4$. Therefore, the proportion for the aggregate containing 75 per cent sand should be 1:4.4, absolute volumes, or 1:3.3 loose volumes.

Fig. 3 is perfectly general and can be used for designing mixtures equivalent to any assumed base.

The diagrams in Figs. 4, 5 and 6 have been arranged for convenience in proportioning pit-run gravels for three classes of concrete:

Class I, suitable for reinforced concrete in general, water-tight concrete, and base course of concrete pavement. It should range in strength from 2400 to 3000 lb. per sq. in.

Class II, suitable for first class foundations, gravity section piers and abutments for bridges, and base course of non-rein-

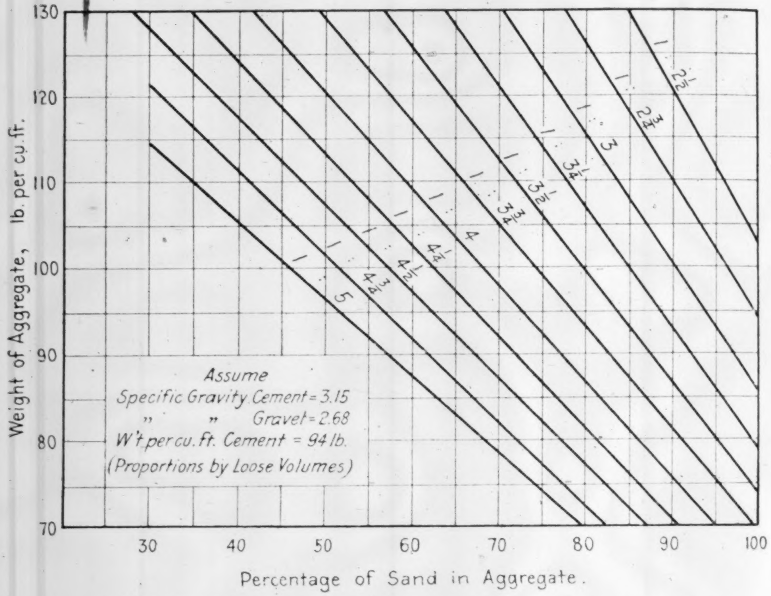

FIG. 4.—Diagram for Use in Proportioning Pit-Run Gravel for Class I Concrete.

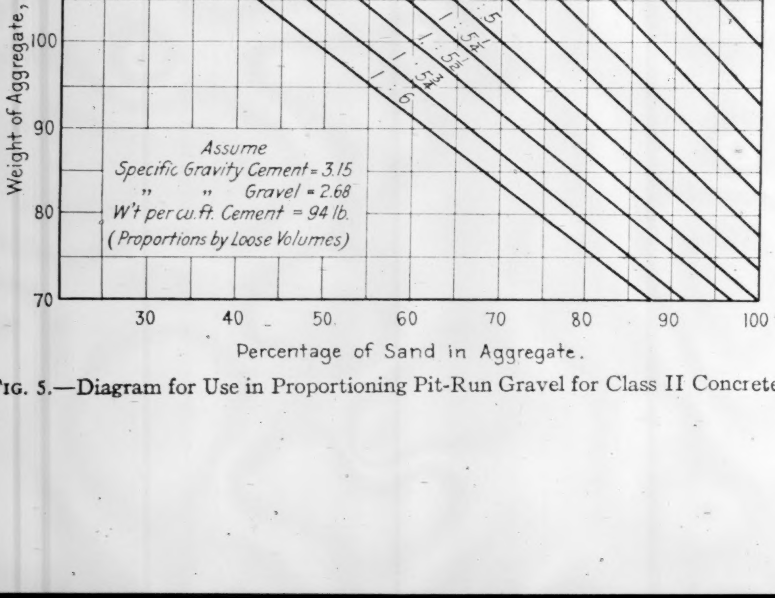

FIG. 5.—Diagram for Use in Proportioning Pit-Run Gravel for Class II Concrete.

forced floors and walks. It should range in strength from 1800 to 2400 lb. per sq. in.

Class III, suitable for large foundations and heavy mass work in general. It should range in strength from 1200 to 1800 lb. per sq. in.

VERIFICATION.

Table IV shows the resulting strengths of laboratory specimens made in accordance with the foregoing principles. It is believed that these results verify the reasonableness of the method of proportioning pit-run gravels described. Series Nos. 48, 49 and 50 were made about one year after series Nos. 46 and 47 from different materials, and by a different operator. The consistency was approximately the same in both groups.

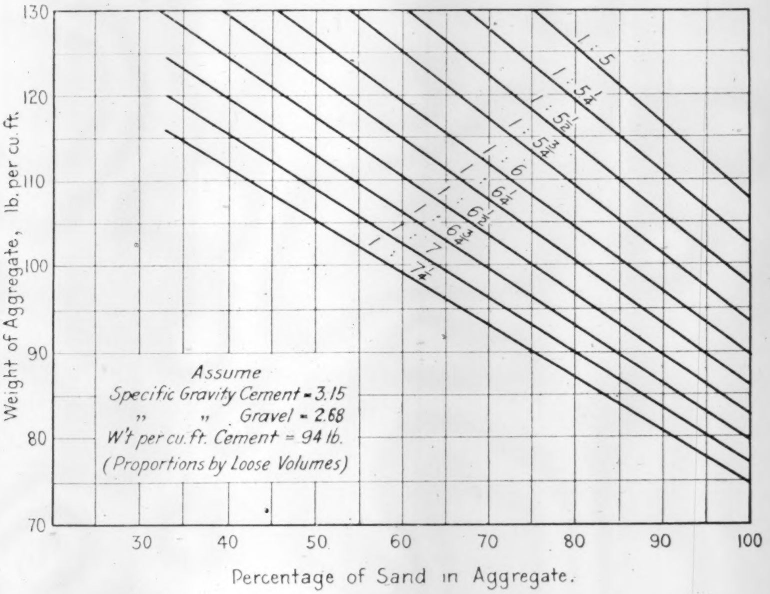

FIG. 6.—Diagram for Use in Proportioning Pit-Run Gravel for Class III Concrete.

Fig. 7, compiled from the averages of numerous tests of various materials and classes of concrete, illustrates in general the decrease in strength when the ratio of cement to total aggregate is made a constant, the increase in strength when the ratio of cement to sand portion of aggregate is constant, and the equivalent strength when the mixtures are proportioned according to the foregoing method.

TABLE IV.—PIT-RUN GRAVEL CONCRETE PROPORTIONED BY THE SAND METHOD.

Concrete Class	Series No.	Material.	Characteristics, Mixed Aggregate.				Proportions.			$\frac{c}{1-d}$	Percentage of Water in Mix, by Weight.	Compressive Strength at 28 days, lb. per sq. in.
			Percentage of Sand.	Weight, lb. per cu. ft.	Fineness Modulus.	Surface Area, sq. ft. per 100 lb.	By Weight.	By Absolute Volume.	By Loose Volume.			
I	48	Sand, No. 21; Pebbles, No. 23.	33	113.9	533	819	1:6.06	1:6.6	1:5	0.374	10.0	1479
			42	114.7	501	978	1:5.49	1:5.92	1:4.5	0.414	10.0	1945
			55	117.5	458	1220	1:4.97	1:5.87	1:4.0	0.403	10.6	2425
			65	115.7	424	1398	1:4.61	1:5.0	1:3.75	0.426	10.3	2465
			75	113.6	392	1575	1:4.23	1:4.60	1:3.5	0.428	10.9	2565
			85	109.3	360	1753	1:3.78	1.4:10	1:3.25	0.433	11.3	2580
			95	106.9	327	1931	1:3.41	1:3.7	1.3	0.434	12.3	2160
II	49		33	113.9	533	819	1:7.27	1:7.90	1:6	0.308	10.1	1343
			42	114.7	501	978	1:6.71	1:7.28	1:5.5	0.340	9.6	1920
			55	117.5	458	1220	1:6.25	1:6.79	1:5.0	0.343	10.2	1800
			65	115.7	424	1398	1:5.54	1:6.01	1:4.5	0.363	10.3	1955
			75	113.6	392	1575	1:5.14	1:5.58	1:4.25	0.367	10.6	2135
			85	109.3	360	1753	1:4.65	1:5.06	1:4	0.356	11.7	2005
			95	106.9	327	1931	1:4.26	1:4.63	1:3.75	0.373	12.4	1860
III	50		33	113.9	533	819	1:8.78	1:9.52	1:7.25	0.269	9.4	1113
			42	114.7	501	978	1:8.54	1:9.26	1:7.0	0.284	9.5	1318
			55	117.5	458	1220	1:8.13	1:8.82	1:6.5	0.270	9.9	1415
			65	115.7	424	1398	1:7.38	1:8.14	1:6	0.287	10.1	1416
			75	113.6	392	1575	1:6.95	1:7.54	1:5.75	0.263	11.2	1225
			85	109.3	360	1753	1:6.40	1:6.93	1:5.5	0.263	12.3	1059
			95	106.9	327	1931	1:5.87	1:6.38	1:5.0	0.260	13.7	1031
I	46	Sand, No. 20; Pebbles, No. 22.	33	115.6	494	756	1:6.15	1:6.8	1:5	0.447	8.8	3120
			42	115.0	468	915	1:5.50	1:6.3	1:4.5	0.490	8.6	3290
			55	114.4	431	1142	1:4.87	1:5.53	1:4.0	0.536	8.8	3260
			75	112.5	374	1495	1:4.16	1:4.73	1:3.5	0.602	9.3	2970
			96	102.5	320	1839	1:3.27	1:3.8	1:3	0.604	10.8	3090
III	47		33	115.6	494	756	1:9.22	1:10.3	1:7.5	0.231	7.7	2000
			42	115.0	468	915	1:8.56	1:9.7	1:7.0	0.293	9.1	1810
			55	114.4	431	1142	1:7.91	1:9.0	1:6.5	0.316	9.25	1950
			75	112.5	374	1495	1:6.88	1:8.0	1:5.75	0.334	10.6	1580
			95	102.5	320	1839	1:5.45	1:6.3	1:5.0	0.371	11.0	1760

The writer expects further to verify the method by making and testing field samples from a large number of jobs on which such material is used.

APPLICATION.

The mere fact that pit-run gravel is ordinarily not a well-graded material, is not an insuperable obstacle to its use. All that is required is its use with the right amounts of cement and water. The principal difficulty is the fact that the product of a pit is often extremely variable as regards grading. Nevertheless large amounts of this material are being used, and since in many cases great economy results from its use, it would seem that engineers should be prepared to lay down rules for the proper handling of this material.

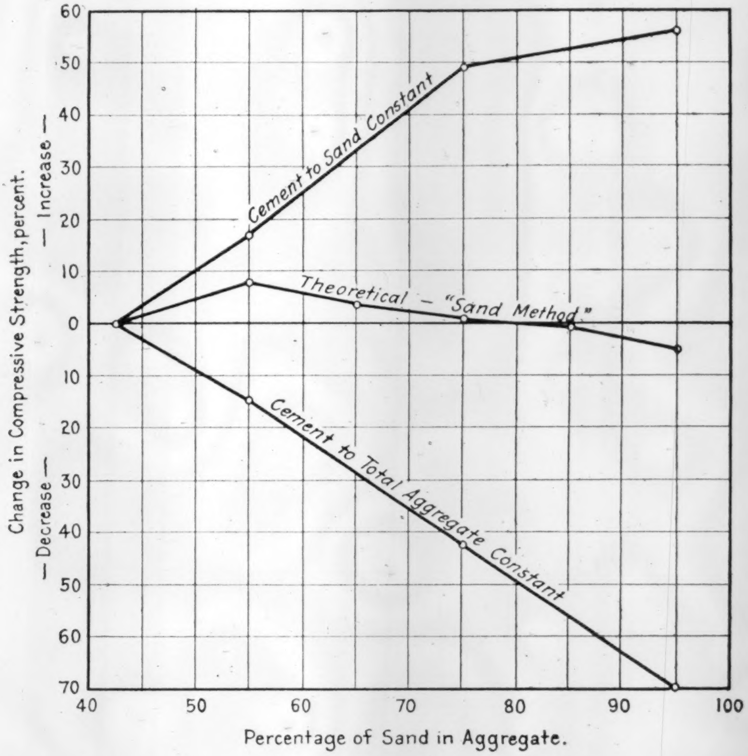

FIG. 7.—Variation in Strength of Gravel Concrete, when Proportioned by Three Methods: (*a*) Cement to Total Aggregate Constant, (*b*) Cement to Sand Constant, (*c*) the Sand Method for Equivalent Mixtures.

This investigation was undertaken by the Engineering Experiment Station of the Iowa State College, at the request of the Iowa State Highway Commission, and their present specifications for the use of pit-run gravel are based upon this work.

An important advantage of the method of proportioning described in this paper is the simplicity of the field tests required. The percentage of fine aggregate (or sand) in the gravel, and the weight per cubic foot, can easily be determined with simple apparatus.

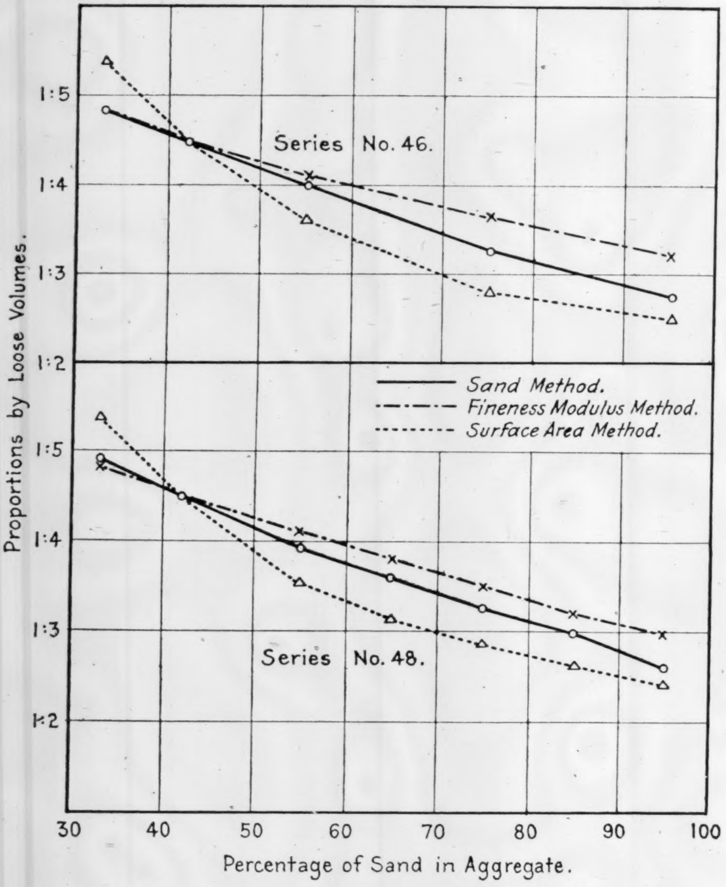

FIG. 8.—Relation between Three Methods for Deriving Proportions to Yield Concrete of Equivalent Strength, "Fineness Modulus," "Surface Area," and the "Sand" Methods.

In practical use, frequent analysis must be made and the proportions changed as often as is necessary to agree with the variations in the material.

COMPARISON WITH FINENESS MODULUS AND SURFACE AREA METHODS OF PROPORTIONING.

Fig. 8 shows a comparison between three methods of proportioning pit-run gravels to produce concretes of equivalent strength, the "Sand" method, as described in this paper, the "Fineness Modulus" method of Abrams, and the "Surface Area" method of Edwards. The proportions necessary to use with gravels containing various percentages of sand, to make concrete equivalent in strength to that of a $1:4\frac{1}{2}$ mixture in which the gravel contained 42 per cent of sand, were computed by each method. The materials, and approximately the mixtures, are those shown in Table IV.

The proportions shown on this diagram are the theoretical mixtures as computed. In the greatest number of instances in which this material is used, it will not be practicable to state the proportions any closer than the nearest half or quarter part of aggregate. When the proportions in the diagram are changed so that the parts of aggregate to one part of cement conform to the nearest quarter part, it will be found that there is very little difference between the "Sand" and "Fineness Modulus" methods. The "Surface Area" method appears to call for somewhat richer mixtures.

DISCUSSION.

Mr. Williams. Mr. G. M. Williams (*presented in written form*).—We believe it is recognized by engineers that concretes should have the same consistency, workability, or flowability in order that conclusions can be drawn from the resulting compressive strength tests. On any concrete work there is some minimum consistency or flowability which must be obtained and used under the usual commercial methods of mixing and depositing concrete, and in the laboratory aggregates which are being compared should be made up in concretes having the same qualities of workability or flowability. It is also generally recognized that, with other conditions equal, strengths of concretes vary greatly with the water content and an excess of mixing water over the quantity required under proper methods of mixing and placing may reduce the strength to a small percentage of what might be attained.

Therefore it seems that any proposed method or theory for proportioning concrete should give consideration to the water factor and take into account the various other factors in the mix which cause variations in the amounts required.

In his summary Mr. Young states that the fineness modulus of an aggregate varies approximately as its surface area. Our experience shows this to be an erroneous conclusion. We find that for any given fineness modulus the surface area per unit weight of material may vary from 300 to 500 per cent, depending upon the gradation of coarse and fine particles.

It is further stated in Mr. Young's paper that the quantity of water needed is that which is required to reduce the cement to a paste plus the quantity necessary to wet the surfaces of the particles of aggregate. To give the desired consistency the formula $W=xC+L$ is proposed. We have found that a formula of this type does not result in concretes of equal consistencies, but does result in concretes having the same ratio of mixing water to cement, and having wide differences in consistency or flowability.

Mr. Young states that aggregates having the least surface areas will require less water, which we find to be true; but the

Mr. Williams. formula fails to give consideration to this variation, with the result that comparable concretes having the same flowability are not obtained. For any group of aggregates which are tested with the same ratio of cement to surface area in the manner that this method provides, the water formula might as well be expressed in terms of the weight or volume of cement and calculated once for all the aggregates of the group.

For aggregates having good concrete-making qualities under ordinary methods, we find that the surface area method results in wide variations in richness of mix, as for example a 1:6 proportion for an aggregate with a low surface area and a 1:2 proportion for an aggregate having a high surface area. Any constant water-cement ratio which may be selected will result in wide differences in consistency or flowability. If the lean mixture is workable and plastic the richer one will be soupy, or if the richer one is given a proper flowability the leaner mix will be too dry to work. A wide difference in strength is also found with constant water-cement ratio; but this is of secondary consideration, since the concretes varying so in flowability are not comparable.

We are not familiar with any formula for quantity of mixing water which takes into consideration the varying surface areas of aggregates. A constant water-cement ratio does not provide concretes with equal flowability even for rather small variations in gradation of sizes of particles. Our tests indicate that for constant flowability the water required and consequently the water-cement relation varies with the surface area of the aggregate. Such variations in area must result in varying values of the water-cement ratio to obtain comparable concretes and such necessary variations make it difficult to connect up the water-cement ratio, the strength and the flowability factors in such a way as to make them of use as the basis of a method for the proportioning of concrete mixtures.

Mr. Abrams. MR. D. A. ABRAMS.—I shall first discuss Mr. Young's paper and later say a few words with reference to Mr. Crum's discussion of the proportioning of pit-run aggregates.

Mr. Young's theoretical discussion of this subject is very interesting, and he is to be commended on the way in which he has gone about developing the theoretical side first, and outlining

Mr. Abrams. the experimental work on this basis. However, I am not ready to agree with a few things he has said with reference to the relation between the fineness modulus and surface area methods of dealing with concrete aggregates. The relation is not quite so happy as he suggests, for the reason that the widest discrepancy may be found in the surface area of aggregates of the same fineness modulus. Mr. Young showed one table on the screen which I believe is not found in the paper. It showed a constant relation between surface area and fineness modulus for aggregates of different sizes. The relation is correct for this condition. It should be borne in mind, however, that he was dealing with materials such as No. 8–4 and $\frac{3}{8}-\frac{3}{4}$ in. There is a definite relation between the fineness modulus and surface area of aggregates so long as we are dealing with single-sized particles, but this relation no longer holds when we make comparisons between *graded* aggregates. For concrete purposes we are always dealing with graded materials and are not, in general, interested in the properties of single-sized particles. In my paper on "Design of Concrete Mixtures,"[1] reference is made to the mathematical relation between the fineness modulus of an aggregate and the diameter of the particles. It is there shown that the relation for a single-sized particle may be expressed as a constant plus another constant multiplied by the logarithm of the diameter. The constants do not here concern us particularly; they are determined by the sizes of the sieves and the units of measure. For a single-sized particle it is seen at once that the fineness modulus is a function of the logarithm of the diameter of the particle. The surface area is also a function of the diameter, so we have the results that Mr. Young pointed out.

However, the moment we come to deal with graded aggregates a very different relation is found. The relation may be shown by the following:

The expression

$$S = S_0 \left(p_0 + \frac{p_1}{2} + \frac{p_2}{4} + \quad . \quad . \quad . \quad + \frac{P_n}{2^n} \right)$$

gives the surface area of a graded material, where $S =$ the surface area of the total aggregate, $S_0 =$ the surface area of the aggregate

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[1] *Bulletin No. 1* of the Structural Materials Research Laboratory.

Mr. Abrams.

of sizes between the Nos. 200 and 100 sieves, and $p_0, p_1, p_2, \ldots$ are the proportions caught between adjacent sieves of the Tyler series (Nos. 100, 48, 28, 14, 8, etc.).

The expression

$$m = 0p_0 + 1p_1 + 2p_2 + \ldots + np_n$$

gives the fineness modulus of a graded material, where $m =$ fineness modulus of the total aggregate and 0, 1, 2, ... are the fineness moduli of material of sizes Nos. 200–100, 100–48, 48–28, etc., and $p_0, p_1, p_2, \ldots$ are the same as defined above.

It should be noted that $\Sigma p = 1.00$.

The relation of surface area to fineness modulus may then be expressed by the following ratio:

$$\frac{S}{m} = \frac{S_0\left(p_0 + \frac{p_1}{2} + \frac{p_2}{4} + \ldots + \frac{p_n}{2^n}\right)}{0p_0 + 1p_1 + 2p_2 + \ldots + np_n}$$

From the equation it can be seen at once, or proven by trial, that no constant relation exists between S and m as different sets of values of p are chosen. For a given value of S an infinite number of sets of values of p may be found; a similar statement may be made with reference to m.

In the bulletin referred to above a series of tests was given in which aggregates of the same fineness modulus were used, yet we get surface areas varying almost 600 per cent.

The reason that Mr. Young finds such a satisfactory relation between fineness modulus and surface area must be due to the more or less accidental condition that the sands he used conformed to more or less similar gradings. I do not quite understand Mr. Young's reference to range of concrete sands as having fineness moduli of 2.5 to 5.5. Probably that is an error, because it would require an aggregate graded up to about 1¼ in. or so to give the higher value.

I shall not burden you with a prolonged discussion of this subject. An article is published in the June 19, 1919, issue of *Engineering News-Record*, which gives my views in some detail. I should, however, like to point out what seems to me to be serious limitations of the surface area method. In the first place, I see very little theoretical justification for the claim that the

Mr. Abrams. surface area of the particle is a determining factor in the design of concrete mixtures. At first thought it seems convincing that the surface area is significant, but when we analyze conditions we find that the amount of water actually required to wet the surface of sand particles is almost negligible. Very careful tests made by Earl Pettibone[1] show that the amount of water necessary to produce free water on the surface of standard Ottawa sand is about a twentieth of a pint for a cubic foot of sand. Obviously for most concrete materials it would be very much less. These are negligible quantities. The water required to wet the surface, it seems to me, is the only factor that has any bearing on the surface area of particles. The others, such as the quantity of water required to wet the cement and the quantity of water required to produce a plastic mixture, are only remotely related to surface area of aggregates.

In calculating surface areas by the method originally suggested by Mr. Edwards, it seems to be necessary to neglect the areas of the finer particles. It is obvious that the areas of very fine quantities of sand will become enormous when we are dealing with any considerable quantity of material. That seems to be a serious limitation in the application of the method. The calculation of the surface area of the particles in this way begins where our fineness modulus method is finished; in other words, the fineness modulus method seems to me to be very much more simple to apply, and I am convinced that our experimental results will justify confidence in that method.

It should be pointed out that the fineness modulus of an aggregate is used for two entirely different purposes: (1) it enables us to proportion aggregate of different size so as to secure the best total grading; (2) it enables us to deal intelligently with the water proportioning. The method of accomplishing these results is described in the bulletin referred to above.

Now, just a few remarks with reference to the paper on Proportioning of Pit-Run Gravel, by Mr. Crum. Apparently what Mr. Crum has attempted to do is only a rough approximation of the result which can be accomplished by our fineness modulus method. We have used six to eight sieves because we considered that number necessary for proper control of the grading of aggregates for research purposes. For field use and approximate work we have devised a method whereby only the alternate sieves in the usual Tyler series are used (Nos. 48, 14, 4, and $\frac{3}{4}$-in.). The use of these sieves will give a fair approximation of the true sieve analysis. By platting the curve and interpolating the values for the missing sieves, the fineness modulus of an aggregate can readily be calculated. **Mr. Abrams.**

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[1] *Journal*, Am. Chem. Soc., April, 1919.

Mr. Crum attempts to do all this with one sieve. In some instances one sieve probably gives results which are close enough, but it would be very easy to encounter materials which would pass the requirements set by Mr. Crum and still be entirely unsuitable for concrete. For instance, a gravel that contains a larger proportion of very coarse sand would pass the proposed test. I do not see anything about Mr. Crum's method that would prohibit the use of such a material; yet all our experience shows that such an aggregate would not be satisfactory.

Both Mr. Crum and Mr. Young have referred to the density of the concrete and its influence on the strength and other properties. It seems to me that there are three very important objections to attempting to use the density in dealing with concrete mixtures: (1) the density has no particular relation to strength if either the proportions of cement or consistency are varied; (2) the calculation of density of concrete is a very painstaking, laborious job, and one which few engineers can or will do; (3) conclusions based on density of concrete are in the nature of a postmortem; you cannot tell anything about the density until after the concrete is made. What the engineer wants is a method of dealing in a rational manner with the concrete before it is mixed. A method for determining the characteristics of concrete after it is in place is of little practical value.

Mr. Talbot. MR. A. N. TALBOT.—I had not seen the paper of Mr. Young and had not expected to present a discussion, but I will try to say a few words. I said last year, and I believe all will agree, that concrete is a very complicated material. A number of elements which enter into it are very intimately related, the amount of cement, the amount of mixing water, the amount of the surface of the particles, the voids in the materials, etc. I do not think any single one of these can be said to control the distinguishing characteristics or the properties of the concrete.

Mr. Talbot. Within the last few months I have become interested in the question of the surface area of aggregate, and have been making tests at the Laboratory of the University of Illinois on materials having different amounts of surface area. The tests have been limited to specimens having the same amount of cement in the mix; no variation has been made in the proportion of cement. The tests have been limited generally to one consistency. It was thought best to keep to one consistency at the beginning of the investigation because comparisons should be made first on concrete of the same workability or mobility, that being a basic factor in the placing of concrete. The aggregates used were sand and gravel. The "surface modulus" of the aggregates, a term to be explained later, varied from 2 to 30, so that the range in the surface area of the aggregates was considerable. Included in the tests were aggregates with the following maximum size of particles: 2, $1\frac{1}{2}$, $\frac{3}{4}$, $\frac{3}{8}$, and $\frac{1}{4}$ in.

The tests indicate that for an aggregate having a given maximum size of particles the amount of mixing water required to produce a concrete of a given consistency or mobility is equal to a constant plus a term which is dependent upon the surface area. That I believe is brought out very clearly. The smaller the maximum size of particles, the more the water required. That also is brought out clearly. Now, as to strengths; the tests show that the strengths of these concretes, made up to have the same mobility, are also dependent upon the surface area. The results fall nearly in a straight line until an aggregate having a very low surface area is reached, a point where the same workability could not be obtained. The concretes with the smaller maximum particles appear to have a somewhat lower compressive strength for the same surface modulus. Concretes having the same water-cement ratio give nearly the same strength through a part of the range of water-ratio values, but for each maximum size of particle the results diverge from the main curve—this occurring at places along the curve which vary with the maximum size of particle and which are quite far apart.

Mr. Young in his paper has used the surface area of grains for each size of sieve, and has determined the surface area of the particles from these values and a count of the number of particles, and has used these areas in his comparisons. Instead of the

Mr. Talbot.

actual computed area of the particles I have been using what may be termed a "surface modulus." If a series of sieves be used such that the second sieve has a clear space twice as great as the first and each succeeding sieve twice as great as the preceding one (there being little material finer than that which will not pass a sieve half the opening of the finest sieve), and if it be assumed that the mean diameter of the particles that pass a sieve and are retained on the next larger size is twice that of the corresponding particles of the next smaller size, and also that the particles are similar solids both in respect to volume and surface area (as is indicated to be true by the data given by Mr. Young), it can readily be shown analytically that the total surface area of the aggregate is proportional to the sum found by adding the percentage passing the smallest sieve, one-half of the percentage retained on this sieve but passing the next larger sieve, one-fourth of the corresponding percentage between the sieve last named and the next larger, followed with coefficients of one-eighth, one-sixteenth, one-thirty-second, etc. If p_1 represents the percentage passing the No. 100 sieve, p_2 that between the Nos. 100 and 48 sieves, following the corresponding percentages between sieves for Nos. 28, 14, 8, 4, etc., to the largest size of particle, the sum

$$s = p_1 + \tfrac{1}{2}\,p_2 + \tfrac{1}{4}\,p_3 + \tfrac{1}{8}\,p_4 + \tfrac{1}{16}\,p_5 + \tfrac{1}{32}\,p_6 + \tfrac{1}{64}\,p_7 + \tfrac{1}{128}\,p_8, \text{ etc.}$$

will be proportional to the surface area of all the particles (if there is little material finer than the No. 200 sieve), and may be termed the surface modulus. When moduli obtained in this way are plotted against surface area obtained by count and calculation such as those made by Mr. Young and others, the relation is found to be a straight line, indicating that this surface modulus closely represents the surface area of the aggregates. It gives a convenient way of comparing surface areas, and will be found useful in getting at the relative areas of fine and coarse aggregates and their combinations. Just where the series should begin and end may need study.

In regard to the fineness modulus which has been referred to: if we take the same analytical method and go through a similar process, it will be found that the complement of the fineness modulus obtained by subtracting the fineness modulus

Mr. Talbot. from 10 if ten sieves are used (from 9 if nine sieves are used, etc.), will be given by the equation

$$m = p_1 + 0.9\ p_2 + 0.8\ p_3 + 0.7\ p_4 + 0.6\ p_5 + \ldots\ldots\ldots\ 0.1\ p_{10}.$$

It is evident that fineness modulus gives a much greater emphasis to the larger particles than does the surface modulus or than will be the case for surface areas; for example, for the surface modulus 1/512 is used where the complement of the fineness modulus uses 0.1. For a regularly graded sand, the fineness modulus and the surface modulus would bear some relation to each other; one would be a function of the other. It is evident that the fineness modulus gives too much importance to the larger particles, if we are to use it as in any way proportional to the surface area. For mixed aggregates of varying gradation, the fineness modulus and the surface modulus are not comparable. In fact, as is shown in the table given by Mr. Abrams in *Bulletin No. 1* of the Structural Materials Research Laboratory, in aggregates having the same fineness modulus one may have six times the surface area of another.

This brings us to the question as to which is more nearly representative of water requirements and of other properties, the surface modulus or the fineness modulus. As far as I can find out from the tests I have seen and have been able to make, comparisons of the surface (or surface modulus) give much better criteria than fineness modulus. This seems to be true in regard to the quantity of water required to produce a given mobility, in regard to strength relations which may be expected, in regard to uniformity of results, and in regard to the peak where the values begin to turn backward. Some have thought that the fineness modulus is representative of the amount of water which is needed to produce a given mobility. Take the tests referred to in Table II of the bulletin just referred to: attention should be called to the fact that the aggregate here which has a fineness modulus of six is, on the whole, a rather coarse material, well up to the limit of what could be used in workable concrete. Those combinations of aggregates which have a very low surface area are not easily worked. On the same ground that aggregates which do not give workable concrete are thrown out in getting at the laws of strength, these aggregates should not be used

Mr. Talbot

in getting at the laws of mobility. Taking those aggregates of this table that come down to a workable basis for concrete, our tests with material of the same sieve analysis indicate that the water content required to produce a given consistency or mobility for the aggregates with the higher surface areas given in this table, is 25 per cent more than that required for those aggregates having only one-third as great a surface area, the fineness modulus being the same in the two cases. Using the same amount of water for aggregates of the same fineness modulus as was used in the tests reported in the table, there is quite a difference in strength; if the same mobility and a consequent varying water content had been used, the discrepancies in strength would have been much greater.

The discussion all goes to show, it seems to me again, that this is a complicated question. We should feel encouraged by the information coming out and the fact that the subject is being studied by so many different people in so many different ways. I am becoming hopeful that we shall soon be able to find laws which will tell us definitely in advance something about what properties we can get in concrete. One thing that has not yet been studied very much is what the relation must be between the finer particles and the coarser particles of the aggregate in order to get a required amount of lubrication so that the concrete may easily be made sufficiently mobile. It is to be expected that there will be some proportion of the finer particles to the coarser which for a given amount of cement (also acting as a lubricant) and the necessary amount of mixing water will produce a desired quality of concrete. When will a combination of fine and coarse aggregate cease to be workable? There are other questions of the same sort.

Mr. Thompson.

MR. SANFORD E. THOMPSON.—I have prepared no discussion on these papers and do not propose to take up any of the details that have been discussed. I do wish to say a word, though, on the importance of this whole subject. This matter is one of the most important questions in engineering construction to-day, and it is important because of its bearing on cost. Concrete is entering into almost all classes of structures, and yet we find an utter disregard of any economic treatment.

Most reinforced concrete design is based on an assumed

Mr. Thompson. compressive strength of 2000 lb. per sq. in. in 28 days, yet we find in practice that the actual strength of concrete with the same proportions of cement, sand and stone varies from 1000 to 3000 lb. per sq. in. or even higher. On the one hand we have a concrete with an insufficient factor of safety, especially at early periods, and on the other hand we find concrete which costs scarcely more than the other but is much stronger than is necessary.

Now the chief causes of this variation of strength have been pointed out in the papers presented here and elsewhere as grading of the aggregate, method and time of mixing, amount of water used in mixing, and curing. Just as soon as the principles of producing concrete of high strength are put into practice commercially and on a wide-spread scale, we shall be able to use leaner mixtures for a given strength and thus reduce appreciably the cost of the concrete. Just at the present time this is of the most vital importance in construction so as to balance, at least in part, the high cost of materials and labor.

It has been known, of course, for a long time that the grading of the aggregate and the amount of water does affect the strength of the concrete to a very large degree, and such papers as those presented aid in developing practical results. The formula of Mr. Crum was brought out by Feret in France, in the Annals des Ponts et Chausser in 1892, and the concrete formula with certain modifications has been used more recently in "Concrete Plain and Reinforced." The fact that a certain sand requires a definite amount of water for a given consistency also was brought out by Feret.

A point which must not be lost sight of in studies of concrete mixtures is the fact that cement is practically the same as sand when grading and consistency is considered; that is, if one takes a sand made up of particles as fine as cement particles, this sand requires the same amount of water to produce a given consistency as the cement does. Therefore, in formulating laws for consistency and grading the cement must be taken as a part of the sand.

Mr. Edwards. MR. L. N. EDWARDS (*presented in written form*).—In a theoretical study having for its object the development of a well balanced, practical method for designing concretes, we are inevitably bound to recognize two natural divisions of the subject.

Mr. Edwards.

These divisions are, however, very closely interrelated and cannot be considered altogether independently. One of these involves a consideration of the physical and chemical properties of the constituent materials, the other a consideration of the methods and operations which enter into the "transition" or "making" stage. Experience has amply proven that the latter may operate to vitalize and to develop in the finished product all the latent functions possessed by the materials; or, on the contrary, they may serve to render these functions wholly or in part impotent, inert and useless. It is a situation in which we have two groups of forces tending under favorable conditions to coordinate and under unfavorable conditions to disrupt. Naturally enough this dual condition has resulted in a certain amount of confusion in the interpretation of results obtained from experimental tests.

The theoretical studies made by Mr. Young have shown quite conclusively that the grading of the aggregate, or more specifically its surface area, bears a very definite relation to the strengths of mortars and concretes. The relations which he has shown to exist between the surface area and the cement and the water contents of the mix are fundamental. Further studies and experimental tests will show a still wider application of this surface area factor than has yet been developed.

When the surface area method of proportioning mortar and concrete mixes was presented at the 1918 annual meeting of this Society,[1] the discussion brought forth the claim that the grading of the aggregate and consequently its surface area influenced the strength of a mortar or a concrete only to the extent of fixing the quantity of water necessary to produce a plastic mix. In view of my own investigations and the conclusions drawn from them I was prepared to accept this notion only with definite limitations rather than in the "blanket form" in which it was offered.

It is obvious that if we are to establish a uniform method for the testing of the mortar and concrete-making qualities of sand and stone aggregates we must aim to eliminate factors depending upon the judgment and personal equation of laboratory operators. The visual or "guess-by-eye" determination of a

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[1] L. N. Edwards, "Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates," *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 235 (1918).

Mr. Edwards. "plastic mix" is too indefinite for adoption as part and parcel of such a method. The speaker recognizes fully the importance of the water content of mortar and concrete mixes both as regards its proper function and its influence when used in excess of that required for the fulfilment of that function. However, he is not prepared to believe that the interpretation of its full effect is based upon the relation of the water to the cement contained in the mix, that is, upon the water-cement ratio. The fundamental principles of the surface area method of proportioning preclude the unqualified acceptance of this ratio. In so far as the surface area method is concerned, it is an indirect function rather than a primary one. It varies rather indirectly with the richness of the mortar or the concrete mix.

It is of interest to note that in Table II of his paper Mr. Young has brought out very clearly the effect of the cement content as tending to vary the water-cement ratio and has shown that for uniformly moist mixes this ratio is variable. His conclusions are in full accord with the consistency theory of the surface area method.

The theoretical studies described by the author do not touch upon the effect of sandy dust (material passing a No. 100 sieve) in its relation to the water content of mortar and concrete mixtures. In the very limited concrete tests described in the speaker's paper read at the last annual meeting, the dust content of the sand aggregate was treated as having the same surface area as an equal portion of material passing a No. 80 and retained upon a No. 100 sieve and the cement content was proportioned accordingly. As regards the water content of the three concrete mixes described, the paper referred to states: "The water content of the mix was sufficient to produce a saturated, sticky, semi-plastic mortar showing no free water." In other words, the water content was determined by visual examination rather than by a specific rule. The speaker's investigations of the surface area method had not then extended to the development of a rule or formula for the determination of the water content of a uniformly moist concrete mix. However, the results of the tests appeared to be amply consistent to indicate the adaptability of the surface area method to concrete mixes and for this reason alone they were included.

Mr. Edwards

Tests made within the past six months with the object of obtaining information relating to the effect of sandy dust have shown quite conclusively that the assumptions just referred to were entirely wrong in principle. Speaking briefly, these tests show that in proportioning the cement content no allowance should be made for the surface area of dust material and that the water allowance for moistening the dust is nearly equal per unit of weight to that required per unit weight of cement. In other words, we must treat the dust as a "dilutant" or "extender" of the cement rather than as a component part of the sand aggregate. Incidentally it may be said that these tests have shown ample evidence of both the reliability and the advisability of the common practice of limiting the dust content, by weight, to approximately five per cent of the sand aggregate.

For a proposed concrete structure, the consideration of possible sources of supply of aggregates frequently involves the laboratory examination of the concrete-making qualities of two or more different aggregates varying in their granulometric composition and other physical properties. The field conditions attending the mixing, handling, placing and finishing of the concrete, as well as the ultimate strength, durability, etc., of the concrete producible from them require that the relative merits of these aggregates be determined under conditions eliminating variations in the relative plasticity and the final strength of the cement matrix which performs the function of holding together the particles of the sand and stone aggregates. When the aggregate contains sandy dust it is important that allowance be made for the quantity of water required to moisten it.

Having determined under uniform conditions the relative concrete-making values of the materials, the question of their adaptability to the production of workable, plastic concrete mixes capable, in the "transitory" stage, of being formed with a reasonable amount of work into the various shapes required in its adaptation to the construction of bridges, buildings, roadways, etc., can be fully and systematically considered. The quantity of water required for absorption by the aggregate and for moistening its surfaces remaining constant, an increase in the water content over that used in the tests produces a dilution of the cement paste which ultimately results in a weakening of the

Mr. Edwards. cement matrix. Unfortunately many investigators have overlooked the basic importance of the cement matrix and have evolved their investigations upon the assumption that the mobility of the mix is a primary rather than a secondary factor. The very nature of the component materials and the varied proportions in which they are used render such an assumption untenable.

The determination of the effect upon the strength of mortars and concretes resulting from an increase in the water content has been the object of studies and tests made by several investigators, so that a considerable volume of information is now available. Doubtless the tests, formulas, etc., reported by D. A. Abrams, Lewis Institute, Chicago,[1] are the most complete, exhaustive and reliable.

Having discussed, at least to a limited degree, the fundamental requirements for the investigation of aggregates, it will not be amiss to indulge in a brief consideration of the conditions which are of vital importance to the laboratory testing of concretes and to the establishment of standard methods and practices. While several conditions of lesser importance might be enumerated, the three most important, basic conditions entering into comparative tests are the following:

1. The water content of the mixes must be sufficient to permit the production, without loss of water, of uniformly sound, well-molded specimens.
2. The water content of each mix must be so proportioned as to produce for a given cement a uniformly strong cement matrix.
3. The cement content of each mix must be so proportioned as to provide a uniform and equal quantity of matrix in relation to the surface area of the aggregates.

In a series of tests adapting the principles just mentioned to laboratory conditions it has been found that concrete mixes containing uniform broken stone aggregate, sand aggregates differing in their granulometric analyses (their surface areas varying from 1830 to 2490 sq. ft. per 100 lb.), and with cement contents varying, by $\frac{1}{2}$ lb., from 1 to 4 lb. per 100 sq. ft. of surface

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[1] "Effect of Time of Mixing on the Strength of Concrete," *Proceedings*, Am. Concrete Inst., Vol. XIV, 1918.

Mr. Edwards.

area of total aggregates, produced generally excellent working conditions when the water content of the mixes was proportioned as follows:

Water to moisten cement = weight of cement multiplied by the percentage of water required to produce normal consistency paste.

Water to moisten surface area of aggregates = 12 cc. per 1000 sq. in. = 0.381 lb. per 100 sq. ft.

Water to moisten dust, if any, = 0.381 lb. per 100 sq. ft. of surface area, its surface area being assumed to be equal to that of sandy material passing a No. 100 sieve and retained upon a No. 200 sieve.

In these tests the concretes produced from lean mixes containing 1 lb. and 1½ lb. of cement per 100 sq. ft. were harsh and required an extra amount of labor to effect the placing in the molds. All other mixes were plastic, the cement paste which they contained being sufficient to lubricate the surfaces of the aggregates. The fat mixes containing over 3 lb. of cement per 100 sq. ft. could have been easily placed in the molds had they contained a slightly less quantity of water. Economy of construction requires that the increased strength thus attainable be taken account of in actual field construction operations.

The origin and development of the water factor for moistening the surfaces of the aggregates and dust will be described a little later by the aid of diagrams.

Surface Area vs. Fineness Modulus.—At practically the same time that Mr. Young was seeking to establish a mathematical relation between surface area and fineness modulus, I was engaged in a somewhat similar effort, not with the object of correlating these methods, but, instead, of finding out just how fineness modulus short-circuited the surface area, as was claimed at the last annual meeting. Just how much efficiency is lost by the short-circuit is not clear. Fig. 1 shows the results of studies made with over fifty natural sands. It gives the impression that possibly the fineness modulus is intermittently or otherwise "grounded" on surface area. However, like the author of the paper under discussion, I was unable to establish a definite mathematical relation.

Reverting now to our consideration of the water content

Mr. Edwards. of the concrete test mix in its relation to the surface area of the aggregates, it is a well-known fact that while the weights of sands vary with the character of the rock materials from which they take their origin and also with their granulometric composition, yet, for any given sand, its weight per cubic foot when dry is greater than its weight when wet, provided, of course, that in each case the sand is shoveled into the measuring receptacle. This condition holds true even when the wet sand is subjected to a moderate amount of compacting.

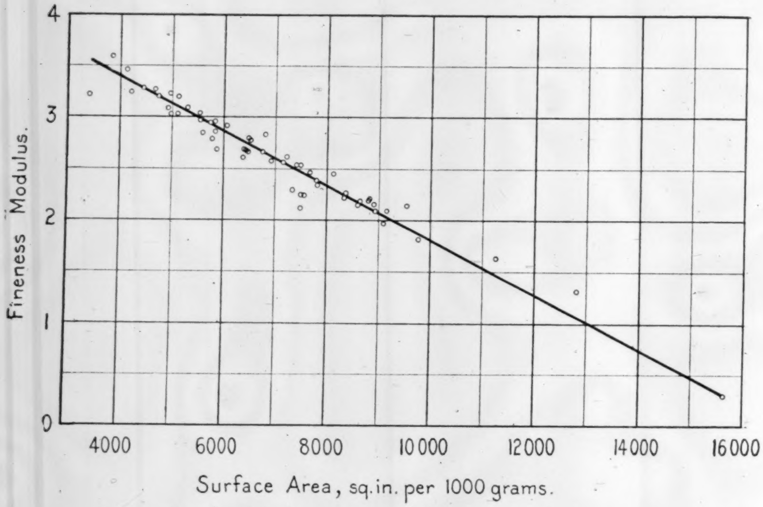

FIG. 1.—Surface Area vs. Fineness Modulus.

Approved practice in mortar and concrete testing is based upon the use of weighed quantities of dry aggregate and only upon this basis can the test results be properly interpreted. It is axiomatic that if results consistent with those secured in the laboratory are to be obtained upon field construction work, the conditions under which the aggregates are measured, more especially the sand aggregate, must be such as to assure reasonable uniformity in the net volume. Notwithstanding this, there is a marked paucity of published data relating to the effect of varying quantities of water contained in sand aggregate used in mortars and concretes. Its absence is evidence that this

Mr. Edwards.

factor has not been given sufficient attention by engineers, architects and construction men.

With the primary object of securing information relative to the "bulking" effect of moisture in sands differing in their granulometric analyses, tests were made by the Department of Works, City of Toronto, Ont., under the direct supervision of the speaker. Paradoxical as it may seem, these tests have shown that the surface area of the sand particles is a direct function of the volume increases produced by varying the quantity of water.

In describing the tests very briefly, it may be said that the volume-weight method was used for determining the quantity of each sand to be used in the tests, the weight being determined in each case from an average of four tests. Natural sands were used. Two series of tests were made upon each sand, the water content being varied in the first in relation to the weight of the sand and in the second in relation to its surface area. A uniform distribution of the water was secured by working the sand with a trowel or other tool. To secure the desired degree of accuracy each intermediate test was repeated four times. From these tests, involving eleven different sands, average volume-increase curves were determined. Fig. 2 shows, for five of these sands, the relation of volume increase to percentage of water content. One per cent of water was amply sufficient to coat thoroughly the surfaces of the sand particles. The "bulking" effect resulting mainly from the cohesive action of this small quantity of water ranged in the tests from 11 to 23 per cent. Permit me also to call attention to two other interesting features of this diagram, namely: the "saturation" stage producing maximum volume when the water content approximates 5 to 7 per cent, and the "flooding" stage at which the volume of the sand is the same as that originally occupied by it when thoroughly surface dried. The water content for the latter varied from 18 to 28 per cent. Careful observation at this stage failed to discover a tendency of the sand to fall below its original dry volume.

The area-water series of tests led to a rather interesting and entirely unlooked for discovery. Fig. 3 shows, for the five sands shown in the previous diagram, the relation of volume increases to the area-water content. Special attention is called to the indications of the existence of a "nucleus" common to all

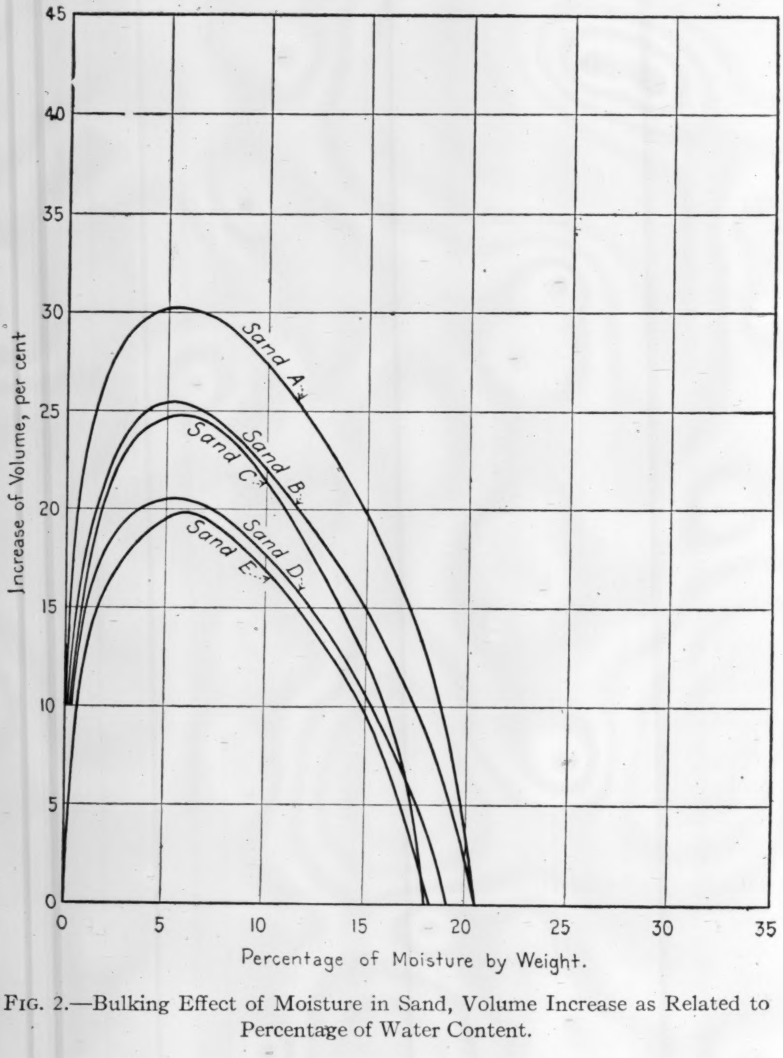

FIG. 2.—Bulking Effect of Moisture in Sand, Volume Increase as Related to Percentage of Water Content.

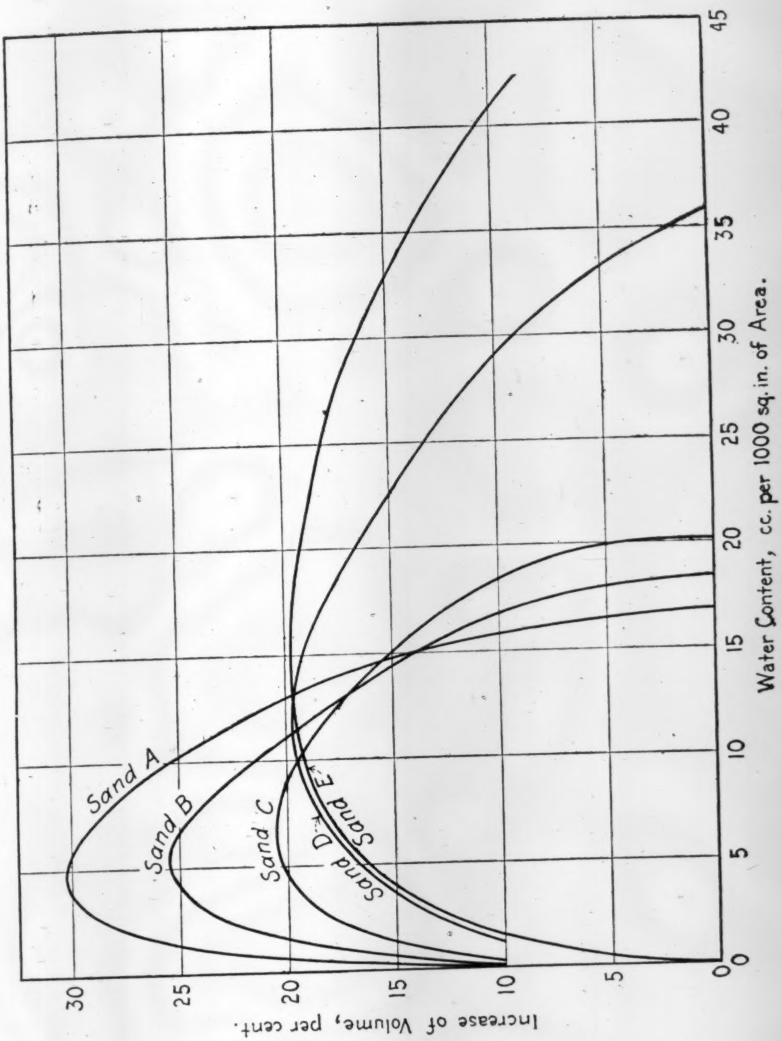

FIG. 3.—Bulking Effect of Moisture in Sand, Volume Increase as Related to Area-Water Content.

Mr. Edwards. the curves. Although the speaker had confidently expected that this series of tests would show the existence of a relation of "bulking" effect to the area-water content, yet this indication of a condition common to all sands tested was quite unforeseen. From a systematic study of the experimentally determined curves, we have deduced the curves shown in Fig. 4. Each curve here shown was derived mathematically from a consideration of all those determined experimentally. Your attention is here called to the actual existence of the "nucleus" indicated in Fig. 3. The water-area ratio of this rather mysterious point is 12 cc. per 1000 sq. in., which corresponds to the water factor (0.381

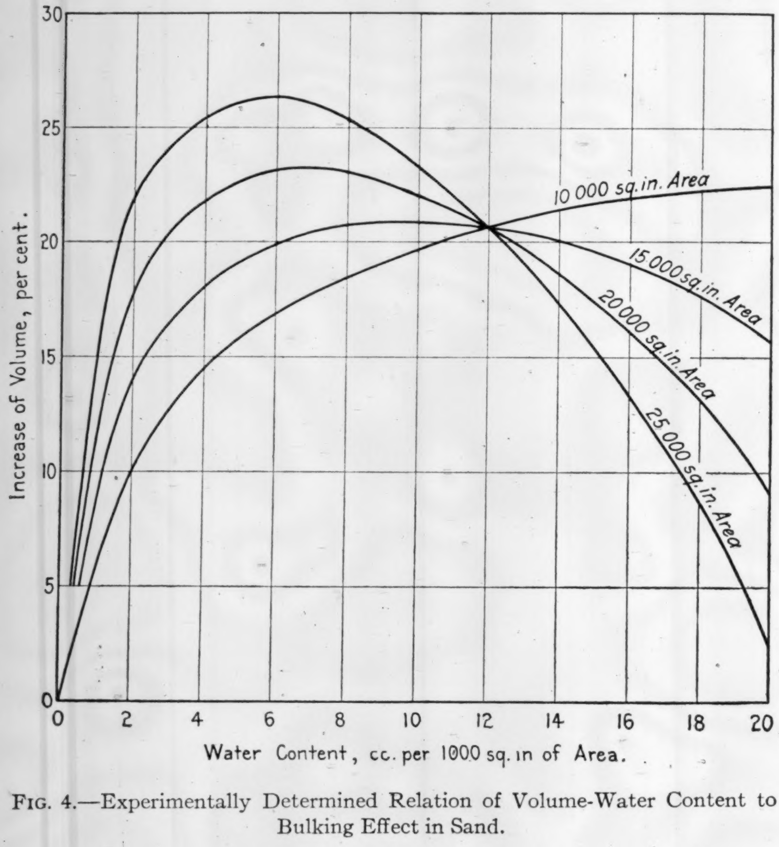

FIG. 4.—Experimentally Determined Relation of Volume-Water Content to Bulking Effect in Sand.

lb. per 100 sq. ft.) used for moistening the surface of aggregates and dust in concrete test mixes. **Mr. Edwards.**

The claim is not made that the volume-moisture condition just described bears a direct relation to the many factors involved in concrete making. However, its actual use in this connection has indicated its efficiency as a working tool. We can, I believe, ill afford to cast it aside without a full and careful trial to prove or disprove its value. It is entirely possible that physical factors other than cohesion and adhesion enter into this peculiar volume-moisture condition. In so far as the speaker has knowledge, its existence has not been previously discovered. However, independent and more recent investigations made by Mr. Young have shown corroborative and unquestionable evidence of its existence.

Since the moisture content in a sand has the rather remarkable effect of increasing its volume by holding the sand particles somewhat rigidly in positions different from those they would readily assume when dry, it seems reasonable to aim to control this "bulking" effect, so far as possible, in test mixes for concrete.

There is no evidence that the "bulking" effect of the moisture in sands has been given consideration either in written specifications or in field operations incident to mortar and concrete making. Its consideration will show the fallacy of the commonly used volumetric method in so far as resulting strengths are affected by the moisture contained in the sand aggregate, and will inevitably lead to the opinion that the adoption of methods and appliances whereby the aggregates will be measured by weight rather than by loose volume will result in a greater uniformity and reliability of the mortars and concretes produced. Important practical considerations render it advisable to continue the present practice of using in concrete mixes a volume of mortar equal to approximately one-half of the gross volume of the stone aggregate.

Messrs. Williams and Davis.

MR. G. M. WILLIAMS and MR. WATSON DAVIS (*by letter*).—With the object of testing the method of proportioning pit-run aggregates proposed by Mr. Crum, the tests presented in this discussion were made.

The tests reported in Table I were designed to duplicate the tests in series No. 48 in Table IV of his paper, so far as possible,

Messrs. Williams and Davis.

with Washington materials; those reported in Table II are based on series No. 47 in the same table.

In making the tests reported in Table III of this discussion, sands of the same gradation as Mr. Crum's sands Nos. 2, 5, and 12 were used in combination with $\frac{3}{4}$-in. Potomac River gravel.

TABLE I.

All concretes have the same flowability of 180 per cent.

Per cent of Sand.	Weight, lb. per cu. ft.	Proportions by Loose Volumes.	$c/1-d$.	Water, per cent by Weight.	Compressive Strength, lb. per sq. in.	
					7 days.	28 days.
33	118.2	1:5	0.412	8.50	1305	2030
42	121.6	1:4.5	0.412	9.22	1500	2150
55	118.5	1:4.0	0.402	10.32	1685	2510
65	116.9	1:3.75	0.399	10.77	1610	2410
75	114.8	1:3.5	0.399	11.42	1540	2355
85	112.4	1:3.25	0.396	12.12	1600	2435
95	107.4	1:3	0.407	13.11	1710	2780

TABLE II.

All concretes have the same flowability of 180 per cent.

Per cent of Sand.	Weight, lb. per cu. ft.	Proportions by Loose Volumes.	$c/1-d$.	Water, per cent by Weight.	Compressive Strength, lb. per sq. in.	
					7 days.	28 days.
33	118.2	1:7.5	0.295	8.17	675	1245
42	121.6	1:7	0.261	9.17	630	1380
55	118.5	1:6.5	0.277	9.94	710	1470
75	114.8	1:5.75	0.236	11.95	590	1310
95	107.4	1:5	0.245	14.01	610	1320

These sands were made by recombining in proper proportions local river sand which had been separated on the proper sieves.

Table IV gives the properties of the local aggregates used. Compressive strengths reported are the average of tests of three 3 by 6-in. cylinders stored in the damp closet. The weights per cubic foot reported and used are 95 per cent of the packed

Messrs. Williams and Davis.

weight obtained by filling a measure in layers one-fourth its height and jolting each layer about 10 times. This figure has been found to be practically equal to an average of the weight of poured-in unjolted material and the packed weight.

Concretes within each series were of equal flowabilities as determined on the "flow table." This apparatus, which measures flow or "consistency," operates by jolting a measured mass of concrete a given number of times so as to cause the mass to flow or spread concentrically outward. The increase in diameter of the concrete is a measure of the flow. The mixes of Tables I and II had a flow of 180 per cent (1.8 times the original diameter), which may be described as a wet road consistency, while the mixes of Table III had a flow of 200 per cent, which is a suitable consistency for reinforced concrete work.

TABLE III.

All concretes have the same flowability of 200 per cent.

Crum's Sand No.	Per cent of Sand.	Weight, lb. per cu. ft.	Proportions by		$c/1-d.$.	Water, per cent by Weight.	Compressive Strength, lb. per sq. in.	
			Absolute Volumes.	Loose Volumes.			7 days.	28 days.
2......	50	122	1:7.63	1:5[a]	0.319	11.82	940	1700
	75	114	1:6.18	1:4.33	0.300	14.22	870	1580
	95	105	1:5.02	1:3.82	0.288	16.78	1055	1830
5......	50	114	1:7.13	1:5[a]	0.372	10.78	1018	1830
	75	113	1:5.68	1:4.02	0.361	12.39	1285	2330
	95	107	1:4.52	1:3.39	0.376	13.62	1480	2500
12......	50	119	1;7.43	1:5[a]	0.356	10.62	1180	2135
	75	116	1:5.98	1:4.12	0.321	12.86	1240	2100
	95	109	1:4.82	1:3.54	0.335	14.72	1310	2330

[a] A 1:5 mix was assumed for the 50-per-cent sand concretes and the proportions for the 75 and 95 per cent concretes computed by Fig. 3 of Mr. Crum's paper.

TABLE IV.

Aggregate.	Per-centage of Voids.	Weight, lb. per cu. ft.	Sieve Analysis: per cent passing.							
			Sieve No. Opening, in.....0.75	...... 0.375	4 0.185	8 0.093	14 0.046	28 0.023	48 0.046	100 0.0058
Potomac River Sand	35.4	106	......	100.00	97.2	87.0	76.6	57.6	17.2	4.4
Potomac River Gravel, ¾ in......	39.6	99	100.0	47.4	3.0	......	......	......	......	......

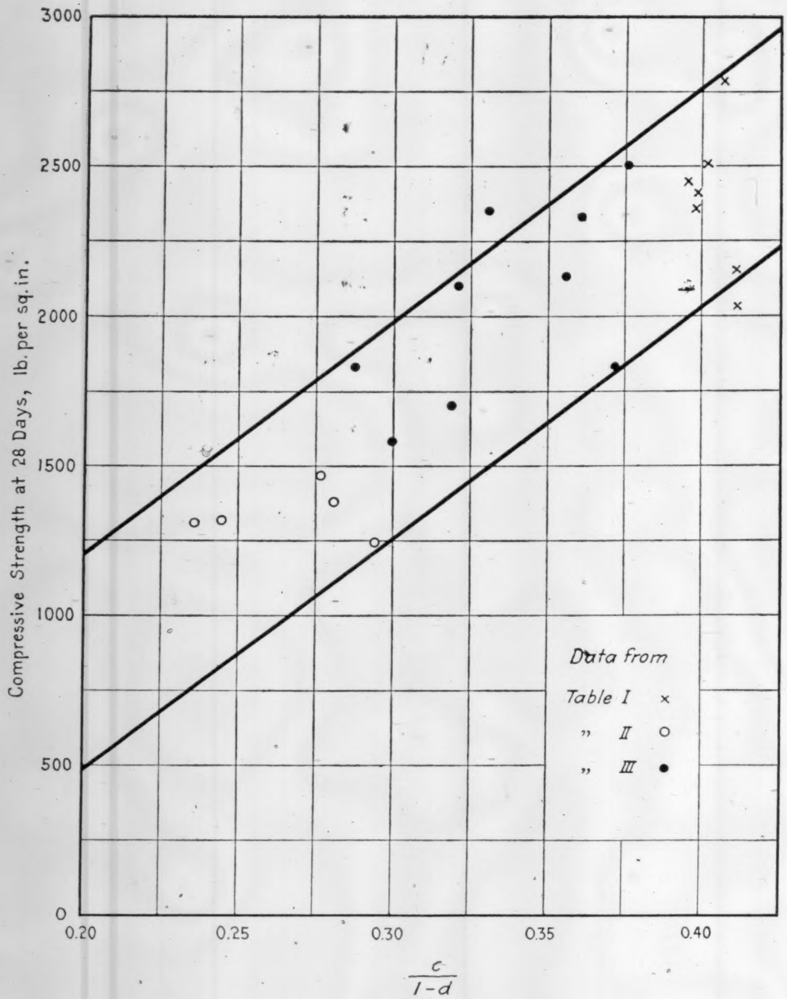

FIG. 5.—Relation between Strength and Ratio $c/1-d$.

Messrs. Williams and Davis.

In general, the strength results obtained in the tests made indicate that the proposed method of proportioning pit-run materials produces concretes of practically equal strength when the aggregates of these tests are used, and equal flowabilities are obtained.

It should be noted that concretes of Table I are comparable and should give equal strengths according to the theory. The same is true of the concretes of Table II. In Table III, concretes made with the same numbered sand should give equal strengths according to the proposed method. The strength results seem to indicate that, generally, the method of proportioning gives strengths that are practically the same. When the sand in the aggregate is less than 50 per cent, there is an indication that the method is not so satisfactory as in the sandier mixes. The method seems to give slightly higher strengths for the sandy mixes, and it is probable that the slope of the curve in Fig. 3 of Mr. Crum's paper could be decreased (mixes be made leaner). The present slope is on the safe side, however.

The assumption that strength varies with $c/1-d$ does not seem to be borne out by these tests. In Fig. 5 of this discussion, the 28-day strengths have been plotted against the values for $c/1-d$ While the trend is toward increased strengths with increased $c/1-d$, the band of points plotted (bounded by lines) is 700 lb. per sq. in. wide, or half of the total difference in strength plotted. This would seem to be too large a variation to justify the statement that $c/1-d$ is a satisfactory and reliable criterion of strength.

It should be noted, however, that the proposed method of proportioning as used in practice does not in any way depend upon or use the assumption that strength is a function of $c/1-d$.

Mr. Abrams.

MR. ABRAMS (*by letter*).—It is interesting to note the similarity of the methods of calculating fineness modulus and surface area. As pointed out by Mr. Talbot, a quantity directly proportional to the surface area of a graded aggregate may be calculated by multiplying a constant by the sum of the quantity—the proportion of material caught between the Nos. 200 and 100 sieves, plus one-half that caught between the Nos. 100 and 48, plus one-quarter that caught between the Nos. 48 and 28, etc. We have employed this method from the first, except that we have chosen the surface area of the material caught

Mr. Abrams. between the Nos. 200 and 100 sieves as the constant. This expression has been stated algebraically in my earlier discussion of Mr. Young's paper.

A very similar expression for the fineness modulus of an aggregate may be derived, and is also given in the discussion just referred to.

A study of these relations will show that the fineness modulus of a single sized particle is an inverse function of the $\log_2$ of the surface area.

It is true, as Mr. Talbot states, that in the calculation of the fineness modulus more weight is given to the larger particles than in the calculation of the surface area. However, I think that his objections will be removed to a great extent when he considers that our method of proportioning water on the basis of fineness modulus does not allow that the quantity of water required for an aggregate is inversely proportional to the fineness modulus; or directly proportional to the fineness modulus subtracted from 10, which he uses for his comparison. By observations on several thousands of tests we have deduced a formula showing the relation between the quantity of water required for a given aggregate and its fineness modulus in which the fineness modulus enters as an exponent.

Mr. Talbot. MR. TALBOT (*by letter*).—In reply to Mr. Abrams' written discussion, the tests referred to indicate that the use of a water content based on fineness modulus, as given by Mr. Abrams, does not give concretes of the same mobility with aggregates which vary in surface area but have the same fineness modulus.

Mr. Young. MR. R. B. YOUNG (*Author's closure by letter*).—After studying the remarks of the various gentlemen who have discussed my paper, I am led to the conclusion that they are in closer agreement than they themselves suspect. Mr. Edwards has found that with concretes, the mixtures of which were of constant mobility, the mixing water used and the strength resulting depended upon the surface area of the aggregate. Both the studies of Mr. Talbot and ourselves agree with these findings, while those of Mr. Williams agree with the latter. Mr. Abrams has found strength and mixing water related to what he has named the "fineness modulus" of the aggregate. This would seem to disagree with the previous conclusions. Our studies

Mr. Young.

have shown, we believe, that the fineness modulus of an aggregate, while in no way related to its surface area, does, in general, vary with it. This being so, then, as far as these points are concerned, the experimental data of each of these investigators agree.

Neither Mr. Williams nor Mr. Abrams agree that this relation between surface area and fineness modulus exists. They cite in support of their position the fact that an infinite number of values of fineness modulus may be found for any one value of surface area and vice versa. This is, of course, true and was not in dispute. But Fig. 1 of the author's paper, which includes some fifty sands graded from 0-$\frac{1}{4}$ in., shows that for these materials the fineness modulus does vary approximately with the surface area. Two diagrams shown at the annual meeting, but not included in the paper because they are so similar to Fig. 1, were of materials graded from 0-$\frac{3}{8}$ in. and 0-1$\frac{1}{2}$ in. respectively. They show the same approximate relation existing. These three charts together represent over 100 aggregates of a wide variation in grading.

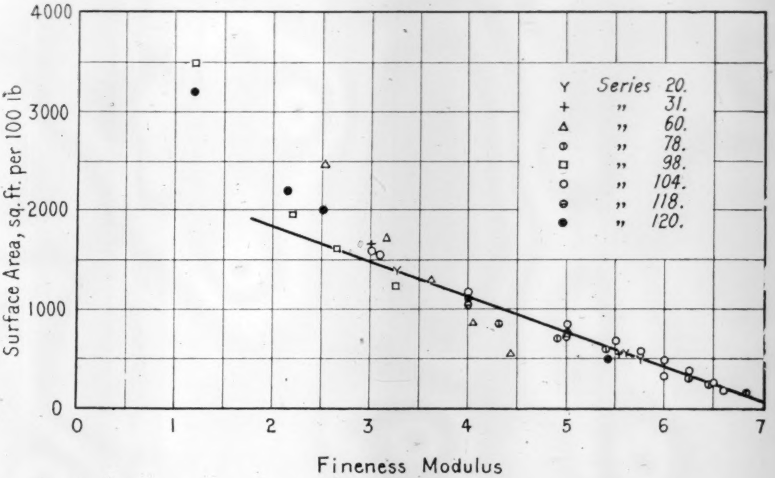

FIG. 6.—Relation between Fineness Modulus and Surface Area of Aggregates (Abrams' Experiments).

We have since plotted Fig. 6 of this discussion from data obtained from the published results of Mr. Abrams' experiments.

Mr. Young. The figure includes all the Elgin sands and gravels of which we have record and include materials graded from 0 - No. 28 to 0-$1\frac{1}{2}$ in. The surface areas of these aggregates were calculated from data obtained from investigations of like materials. This figure also shows the same relation of fineness modulus and surface area but is more general, for it includes material graded to different maximum sizes of particles. Similar charts can be drawn from the data reported by the Bureau of Standards.[1] In view of the foregoing we cannot agree with Mr. Abrams that the "happy relation" between fineness modulus and surface area is due, as he suggests, "to the more or less accidental condition that the sands used conform to more or less similar gradings."

Mr. Abrams suggests that our statement that in Fig. 1 of the paper acceptable concrete sands ranged in fineness modulus between 2.5 and 5.5 was probably an error. Such was not the case. We use a different series of sieves than does Mr. Abrams and consequently the range of fineness moduli would be different from that which he obtains. This leads to what we consider an objection to the use of the fineness modulus in evaluating an aggregate: it is dependent upon the number and sizes of the sieves used. The surface area is not; the same value of surface area can be obtained with any one of the commercial series of sieves in common use because the surface area of an aggregate is a property of the material and is not dependent on the laboratory practice involved.

Mr. Williams is in error when he states that the formula $W = xC + L$ gives no consideration to the variation in the surface area of aggregates. As explained in the paper, L is a function of the surface area and thus the formula fulfils the condition which he finds necessary for uniform mobility. For some time we have been successfully using a formula of this type to obtain concretes of equal mobility.

We are unable to agree with Mr. William's statement that a wide difference in strength is found with constant water-cement ratio. Our tests in the main concur on this point with those of Mr. Abrams. We find there is approximately a parabolic

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[1] *Technologic Paper No. 58.*

Mr. Young.

relation between strength and water-cement ratio for concretes of the same age and made from the same cement and aggregate, regardless of their cement content or grading of aggregate, provided, of course, the concretes are of workable plasticity.

There seems to be a tendency to unduly emphasize the term "water-cement ratio" and not to inquire sufficiently into its meaning. "Water-cement ratio" is simply an index of the quality of the cement paste used to glue together the particles of aggregate. Viewed in this light it is not unreasonable to expect that the relation Mr. Abrams has established should exist. Whatever affects the quality of this cement paste affects its strength and the strength of the concrete in which it is used as a binder. If the quantity of water required to bring a concrete mixture to a given mobility is a function of its surface area, then to maintain the cement paste at a fixed quality under these conditions will require that the cement too must be pro-

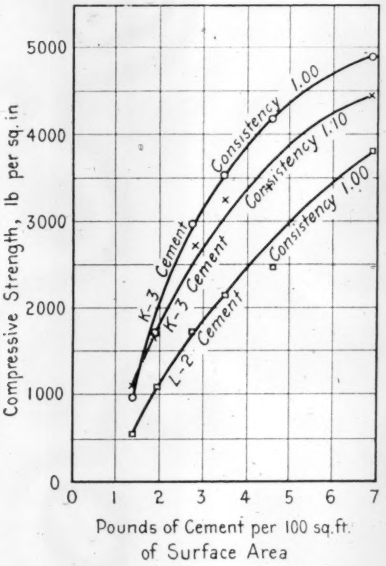

FIG. 7.—Abrams' Tests, Series 120.

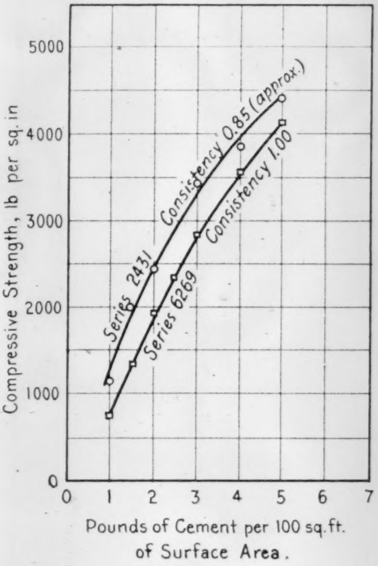

FIG. 8.—Hyrdro-Electric Power Commission Tests, Series 2431 and 6269.

NOTE:—Consistency used by Abrams not comparable with that of Hydro-Electric Power Commission.

Mr. Young. portioned according to the surface area. As Mr. Williams says, this will give rise to different proportions to obtain equal results; however, this is no objection but only the necessary adjustment of proportions to compensate for differences in materials.

In calculating surface area we treat the finer portion of the aggregate, the silt or dust, differently than we do the coarser portion. Our experiments have shown that this fine material is more comparable to the cement than to the aggregate and should not be included in calculating the surface area of the material. We cannot see with Mr. Abrams that this "seems to be a serious limitation in the application of the method." If in this way we recognize the similarity between this fine material and cement which our experiments have brought out, then the method is more to be commended on this score than condemned.

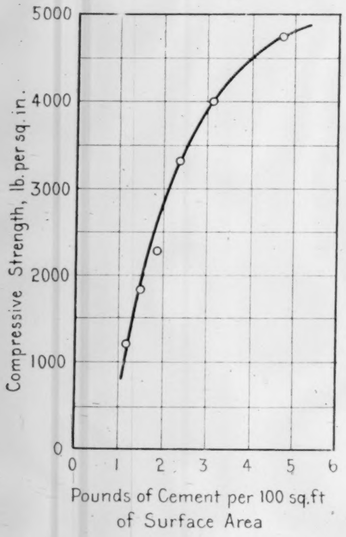

FIG. 9.—Relation between Compressive Strength and Cement Content (Bureau of Standards Tests).

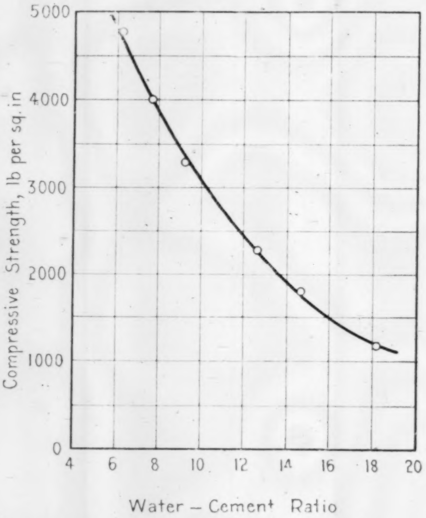

FIG. 10.—Relation between Compressive Strength and Water-Cement Ratio (Bureau of Standards Tests).

Mr. Edwards in his discussion described some tests on the bulking of sands. We have made some extensive investigations on the same question and our results check in every

Mr. Young.

way those reported by him. We have developed a method based on these tests by which we can estimate the surface area of an aggregate by merely observing its moisture-volume relation. This can be done with remarkable accuracy and in so simple a manner that it is quite possible that when this method has been further developed and proved it can be substituted, at least in the field, for sieve analyses.

Returning again to our statement that the investigations of these different gentlemen are in close agreement, we wish to offer in support of our contention Figs. 7 to 10 taken from results obtained by Mr. Abrams, the Bureau of Standards and ourselves. The curves of Figs. 7, 8 and 9 are very similar to Figs. 2 to 6 of the paper. Fig. 10 was plotted from the same data as Fig. 9, but with the strength plotted against water-cement ratio, and gives the relation which Mr. Williams claims does not exist. Fig. 11 was developed from Mr. Abrams' results and shows that for uniform plasticity the water required is proportional to the surface area. This result cannot be explained by the fact that the surface area and fineness modulus have a linear relation, for in the series represented in the chart this

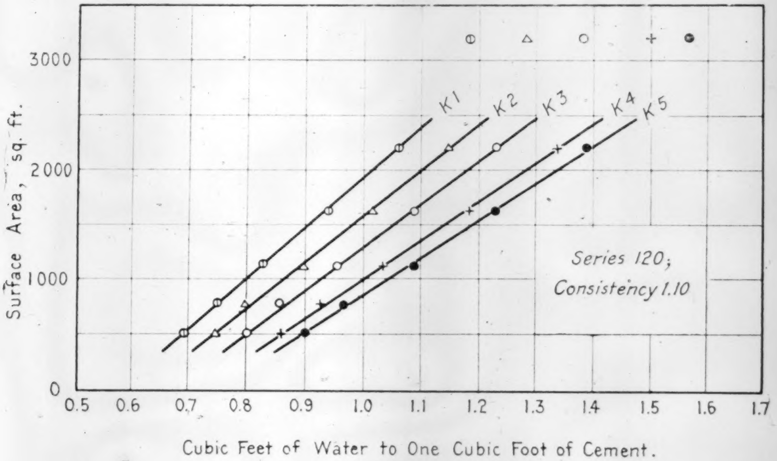

FIG. 11.—Relation between Mixing Water and Surface Area for Constant Plasticity (Abrams' Tests).

Mr. Young. relation was a slight curve (see Fig. 6, series 120). The set of points at the top of the diagram are those corresponding to a very fine material graded from 0-No. 28 and which contained 10 per cent of dust passing the No. 150 sieve. If this dust was compensated for, these points too will lie nearly on the lines drawn.

This paper was not presented with the idea of attacking or in any way disparaging the fineness modulus method of proportioning concrete, but purely as information on a very pertinent topic. We believe the two methods in controversy are much the same thing, but we prefer the surface area conception simply because we find it easier to "put over" in the field. The word "modulus" savors of the laboratory and the technician and the thing it signifies is not likely to be understood by the man using it. (This objection applies equally to Mr. Talbot's "surface modulus.") Its use obscures the "why" of proportioning and places the method on an empirical basis which is undesirable.

Mr. Crum. MR. R. W. CRUM (*Author's closure by letter*).—The author of this paper wishes to make it clear that he is not advocating the use of pit-run gravel in place of washed and screened aggregate in general concrete construction. We have found, however, that such material will of necessity be used in many cases, and that under some conditions a decided economy will result from its use. The paper presents what the author believes to be proper engineering methods for the successful use of such material, and is the result of several years experimental study of the problem.

The method of use recommended in the paper has for its chief advantage the fact that it can be readily and easily applied in the field, with a minimum equipment. No doubt either the "fineness modulus" or "surface area" methods of proportioning may be applied in such cases and of course such detailed methods are of much wider application. Nevertheless extreme simplicity of manipulation is of very great value in having tests made by the ordinary inspector on work situated a long way from laboratory facilities.

Mr. Abrams overlooks the fact that a determination of the weight per cubic foot of the material measured loose is an important step in the method. The weight per cubic foot is also a function of the grading. **Mr. Crum.**

The method does not apply to gravels containing less than 33 per cent of sand, and it has never been applied to extremely coarse sands such as Mr. Abrams mentions. Of course material recognized as not suitable for concrete could not be rendered suitable by this or any other method of proportioning, unless the defects were remedied by other means.

The author agrees with Mr. Abrams that no field use can be made of the density of concrete, but does not see how a theoretical investigation can be made without taking it into consideration. It appears to the author that fundamentally just two factors determine the strength of concrete. One is the actual volume of hard particles in the mass (density) and the other is the extent to which the inert particles are glued together. Of course very many factors influence both of these.

Messrs. Williams and Davis have called attention by letter to an apparent discrepancy in Table III, in that the column of absolute proportions as shown are not exactly the same as if computed by the method of computation given in the paper. The proportions shown in the table were computed from the laboratory record of the exact amount of each material present in each specimen of green concrete. It is entirely probable there would be some discrepancy between these figures and those computed from a measured weight per cubic foot, assumed specific gravity and a loose volume ratio.

MODULUS OF ELASTICITY OF CONCRETE.

By Stanton Walker.

SUMMARY.

Little information has been available concerning the fundamental laws that govern the elastic properties of concrete. Values of modulus of elasticity are used in the design of reinforced concrete structures, from a simple beam to the complicated members of a concrete ship. Knowledge of proper values of modulus of elasticity is, therefore, most important to obtain a rational design.

This report summarizes compression tests on about 3500 6 by 12-in. concrete cylinders. The relation between the modulus of elasticity and strength of concrete was studied for the following variables: size and grading of aggregate, kind of aggregate, quantity of cement, consistency of concrete, age at test, time of mixing, and curing conditions of concrete. The tests show that the modulus of elasticity is affected by these variables in a similar manner as the strength. Tests are reported which show that the gage length over which the deformations are measured do not appreciably affect the determination of modulus of elasticity.

A number of equations have been offered as showing the relation between stress and deformation of concrete under load. A study of the stress-deformation data for our tests shows that this relation may be represented by the equation,

$$s = Kd^n \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where s = unit stress of concrete, d = unit deformation of concrete, K = a constant depending on the strength of the concrete, and n = an exponent, approximately constant.

This equation applies for stresses below 50 to 90 per cent of the ultimate strength, or below what may be termed the "yield point" of the concrete.

There is a general belief that the ratio between the modulus of elasticity and compressive strength of concrete is approximately constant. Tests on concrete of a number of different consistencies, sizes and gradings of aggregate, mixes ranging from 1:15 to about 1:3, and ages ranging from 7 days to 1 year, show that there is a general relation between modulus of elasticity and strength of concrete but that this relation is not linear. The relation may be represented by an equation of the form,

$$E = CS^m \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where E = modulus of elasticity of concrete, C = a constant depending on the conditions of the test, S = compressive strength of concrete, and m = an exponent.

Four different measures of modulus of elasticity of concrete are in more or less common use, as follows:

E_i .... "Initial tangent" modulus;
E_t .... "Tangent" modulus at some load;
E_s .... "Secant" modulus to some load;
E_d .... "Chord" modulus between two loads.

The initial tangent modulus for usual concrete mixtures may be represented by the equation,

$$E_i = 33{,}000\ S^{\frac{5}{8}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

For the tangent modulus at 25 per cent of the compressive strength the equation becomes,

$$E_{t25} = 66{,}000\ S^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

A nomographic chart showing the inter-relation of mix, consistency, size and grading of aggregate, strength, and modulus of elasticity is presented.

A study of data from other sources shows that the stress-deformation relation of a great number of other materials, including various woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds, may be represented by a relation of the same form as that given for concrete in Eq. 1.

MODULUS OF ELASTICITY OF CONCRETE.

By Stanton Walker.

Introduction.

Values of modulus of elasticity of concrete are used in the design of reinforced-concrete structures, from a simple beam to the complicated members of a concrete ship. This means that knowledge of proper values of modulus of elasticity is secondary only to knowledge of proper values of strength if a rational design is to be made. The small amount of available data on this subject has encouraged the writer to present the material contained in this report.

These tests were made as a part of the experimental studies of the properties of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory, Lewis Institute, Chicago.

Modulus of elasticity is usually defined as the ratio of unit stress to unit deformation within the proportional limit. If this definition is interpreted strictly, materials that are not perfectly elastic can have no modulus of elasticity. We therefore prefer to define the modulus of elasticity as:

> The ratio of an increment of stress to a corresponding increment of deformation.

This definition is general for all materials, whether or not they are perfectly elastic. In this sense only perfectly elastic materials have a *constant* modulus of elasticity. Let us apply this definition to the modulus of elasticity of concrete.

There are in more or less common use four distinct measures of this quantity. They are as follows:

1. The "Initial tangent" modulus (E_i); the modulus of elasticity determined by the ratio of stress to deformation as given by a tangent to the stress-deformation curve at its beginning. It will be shown that the initial tangent is equivalent to a secant drawn to 5 to 15 per cent of the compressive strength.

2. The "tangent" modulus (E_t); the modulus of elasticity

determined by the ratio of stress to deformation as given by a tangent to the curve at some stress, ordinarily the working load.

3. The so-called "secant" modulus (E_s); the modulus of elasticity determined by the ratio of stress to deformation as given by a line drawn from the origin of the curve to some stress, ordinarily the working load.

4. The "chord" modulus (E_d); the modulus of elasticity determined by the ratio of stress to deformation as given by the chord drawn between two points on the curve, ordinarily defined by the limits of stresses for working loads. It will be noted that the chord modulus (E_d) is almost identical with the tangent modulus (E_t), hence no study of it is presented.

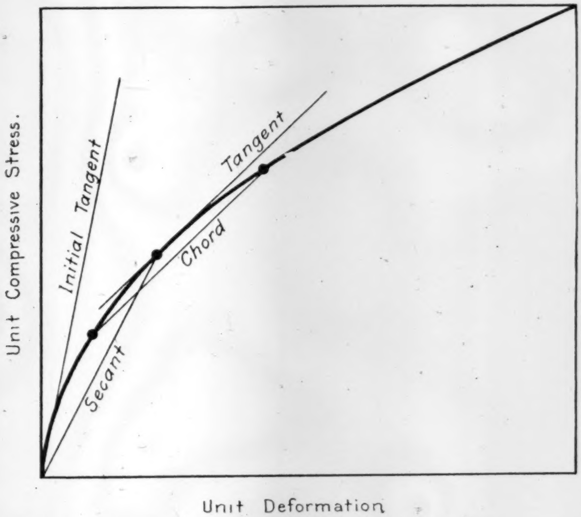

FIG. 1.—Four Methods of Determining Modulus of Elasticity from Stress-Deformation Curve. Curvature is exaggerated to bring out relation clearly.

Fig. 1 shows the graphical conception of the above measures of modulus of elasticity. The relation shown must not be taken as typical since it was necessary to exaggerate the curvature for purposes of reproduction.

Compression tests of about 3500 6 by 12-in. concrete cylinders were selected from nine series of tests made in this Laboratory. These series comprise over 10,000 tests made over a period of 18 months. Representative data are presented which show the effect of the following variables on the modulus of elasticity:

(*a*) Size and grading of aggregate (fine sands to coarse concrete aggregates);
(*b*) Quantity of cement (mixtures varying from 1:15 to neat);
(*c*) Quantity of mixing water (relative consistencies ranging from 0.70 to 2.00);
(*d*) Age at test (7 days to 1 year);
(*e*) Kind of aggregates (pebbles, granite, limestone, and blast furnace slag);
(*f*) Curing condition of concrete;
(*g*) Time of mixing concrete.

Studies were also made to show the variation in modulus of elasticity as affected by:

(*h*) Stress at which modulus of elasticity is measured (up to 50 per cent of the compressive strength of the concrete);
(*i*) Method of calculating modulus of elasticity;
(*j*) Gage length over which deformations were measured (4 to 10 in. on a 6 by 12-in. cylinder).

These tests enable us to establish the form of the relation between stress and deformation. This relation offers an accurate method for the determination of modulus of elasticity, and shows the characteristics of the various measures of this quantity. These tests show that the modulus of elasticity and strength of concrete are affected in the same manner by the variables mentioned above. For a wide range in mixtures, the relation between modulus of elasticity and strength may be represented by a single curve.

In general the data on modulus of elasticity of concrete given in this report were obtained in the course of investigations carried out with other objects in view.

ACKNOWLEDGMENT.

Acknowledgment is made to the firms mentioned below for their courtesy in donating the aggregates, and to Meyer Kaplan and H. L. Flodin, of the Laboratory staff, for help in working up and interpreting the data.

MATERIALS.

The Portland cement used in these tests consisted of a mixture of equal parts of four brands purchased in the Chicago market. The brands were thoroughly mixed by placing one sack of each in a concrete mixer and running for about 1 minute. Details of tests of cement are given in Table I.

TABLE I.—TESTS OF CEMENT.

The Portland cement consisted of a mixture of equal parts of four brands purchased on the Chicago market. All tests made in accordance with standard methods of the American Society for Testing Materials.

MISCELLANEOUS TESTS.

Cement Lot No.	Used in Series.	Concrete Tests Reported in Table.	Fineness Residue on No. 200 Sieve.	Normal Consistency, per cent by weight.	Time of Setting.				Soundness Test (over Boiling Water).
					Vicat Needle.		Gillmore Needle		
					Initial h m	Final h m	Initial h m	Final h m	
3909	83	IV	19.3	23.0	3 15	6 30	5 00	7 25	O.K.
3965	89, 93	V,VI,VII,VIII	18.8	23.0	3 40	7 36	5 15	8 32	"
4035	96, 97, 98, 99	IX,X,XI,XII,	17.5	23.0	3 45	9 00	6 00	9 30	"
4135	104	XIII	18.0	23.0	....	....	....	....	......
4235	114	XIV	19.9	23.0	3 13	6 6	3 57	7 7	"
Average			18.7	23.0	3 30	7 18	5 3	8 8	

MORTAR STRENGTH TESTS.
1:3 Standard Sand Mortar.

Cement Lot No.	Used in Series.	Concrete Tests Reported in Table.	Mixing Water, per cent.	Briquettes, Tensile Strength, lb. per sq. in.					2 by 4-in. Cylinders, Compressive Strength, lb. per sq. in.				
				7d.	28d.	3mo.	6mo.	1yr.	7d.	28d.	3 mo.	6 mo.	1yr.
3909	83	IV	10.3	310	387	408	450	397	1960	3390	4530	4790	4890
3965	89, 93	V,VI,VII,VIII	10.3	242	378	462	440	387	1770	3360	4380	4570	4490
4035	96, 97, 98, 99	IX,X,XI,XII	10.3	246	386	402	424	374	1700	2640	3750	4120	3810
Average			10.3	276	384	418	438	386	1810	3130	4210	4490	4400

The aggregates used were as follows:

Sand and pebbles from the plant of the Chicago Gravel Co. at Elgin, Ill.;
Crushed limestone from the Artesian Stone and Lime Works Co., Chicago;
Crushed blast furnace slag from the Illinois Improvement and Ballast Co., Chicago;
Crushed granite from the Wisconsin Granite Co., Berlin, Wis.

TABLE II.—MISCELLANEOUS DATA OF AGGREGATE.

The sieves were made of square mesh wire cloth manufactured by The W. S. Tyler Co. It will be noted that each sieve has a clear opening of twice the width of the preceding sieve.

Size.	Kind.	Weight, lb. per cu. ft.	Sieve Analysis, Per cent Coarser than Each Sieve.									Fineness Modulus.[c]
			100[a] (0.0058)[b]	48 (0.0116)	28 (0.023)	14 (0.046)	8 (0.093)	4 (0.185)	⅜ (0.37)	¾ (0.75)	1½ (1.5)	
TABLE IV (SERIES 83).												
0–1½	Sand and pebbles...	131	99	97	87	81	74	67	55	40	0	6.00
0–¾	" " " ...	127	99	94	77	64	52	40	24	0	..	4.50
0–4	Sand..............	115	99	90	61	40	20	0	..	..	..	3.10
0–1½	Sand and limestone.	130	100	96	84	75	66	58	51	20	0	5.50
TABLE V (SERIES 89).												
0–1½	Sand and pebbles...	130	100	97	89	84	79	56	50	18	0	5.73
TABLES VI, VII, VIII (SERIES 93).												
0–14	Sand..............	104	98	89	42	0	..	..	..	..	..	2.29
0–8	"	110	99	92	58	28	0	..	..	..	..	2.77
0–4	"	115	99	94	70	48	28	0	..	..	..	3.39
0–⅜	Sand and pebbles...	124	99	95	77	60	44	23	0	..	..	3.98
0–¾	" " " ...	126	100	96	79	75	65	51	31	0	0	4.97
0–2	" " " ...	128	100	99	94	90	86	80	60	40	20	6.69
TABLE IX (SERIES 96 AND 97).												
0–1½	Sand and pebbles...	130	100	98	90	82	76	66	49	16	0	5.77
TABLES X AND XI (SERIES 98).												
0–1½	Sand and pebbles...	126	99	98	91	85	80	73	51	22	0	6.00
0–1½	" " limestone.	121					do.					6.00
0–1½	" " slag......	117					do.					6.00
0–1½	" " granite...	115					do.					6.00
0–28	Sand..............	102	87	33	0	..	..	..	..	..	..	1.20
0–14	"	105	93	87	40	0	..	..	..	..	..	2.20
0–8	"	108	95	90	55	25	0	..	..	..	..	2.65
0–4	"	112	96	93	66	45	25	0	..	..	..	3.25
0–⅜	Sand and pebbles...	121	98	96	82	69	59	46	0	..	..	4.50
0–¾	" " " ...	124	99	97	89	80	74	65	36	0	(1″)[d]	5.40
0–1¼	" " " ...	125	99	98	90	85	80	72	49	17	7	5.90
TABLE XII (SERIES 99).												
0–1½	Sand and pebbles...	134	100	98	90	82	76	67	47	20	0	5.80

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[a] Number of openings per linear inch.
[b] Widths of the clear openings in inches.
[c] Sum of percentages in sieve analyses divided by 100.
[d] Not used in calculating fineness modulus.

TABLE II.—*Continued.*

The sieves were made of square mesh wire cloth manufactured by The W. S. Tyler Co. It will be noted that each sieve has a clear opening of twice the preceding sieve.

Size.	Kind.	Weight, lb. per cu. ft.	Sieve Analysis, Per cent Coarser than Each Sieve.									Fineness Modulus.[c]
			100[a] (0.0058)[b]	48 (0.0116)	28 (0.023)	14 (0.046)	8 (0.093)	4 (0.185)	⅜ (0.37)	¾ (0.75)	1½ (1.5)	
TABLE XIII (SERIES 104).												
0-28	Sand...............	102	87	33	0	..	..	..	..	...	..	1.20
0-14	"	105	93	87	40	0	..	..	..	..	..	2.20
0-8	"	108	95	90	55	25	0	..	..	..	..	2.65
0-4	"	112	99	93	58	33	17	0	..	..	..	3.00
0-⅜	Sand and pebbles...	121	99	95	72	55	44	35	0	..	..	4.00
0-¾	" " " ...	124	100	97	83	70	65	55	30	0	..	5.00
0-1½	" " " ...	126	100	98	87	79	74	69	48	20	0	5.75
0-1½	Sand and pebbles...	119	99	95	69	50	38	25	17	7	0	4.00
0-1½	" " " ...	125	99	96	79	66	59	50	36	15	0	5.00
0-1½	" " " ...	126	100	97	84	75	69	63	43	19	0	5.50
0-1½	" " " ...	126	100	98	87	79	74	69	48	20	0	5.75
0-1½	" " " ...	128	100	98	89	83	79	75	53	23	0	6.00
0-1½	" " " ...	125	100	99	92	87	84	82	57	24	0	6.25
0-1½	" " " ...	120	100	99	95	92	90	88	60	26	0	6.50
TABLE XIV (SERIES 114).												
0-14	Sand...............	105	97	89	34	0	..	..	..	..	..	2.20
0-8	"	108	97	90	50	23	0	..	..	..	..	2.60
0-4	"	112	98	93	60	39	20	0	..	..	..	3.10
0-⅜	Sand and pebbles...	121	99	96	79	68	59	49	0	..	..	4.50
0-¾	" " " ...	124	99	97	86	78	71	65	44	0	..	5.40
0-1½	" " " ...	128	99	98	87	80	74	68	51	18	0	5.75

[a] Number of openings per linear inch.

[b] Widths of the clear openings in inches.

[c] Sum of percentages in sieve analysis divided by 100.

Miscellaneous tests of the aggregates are given in Table II.

The water was from the city water supply obtained from Lake Michigan.

PROPORTIONING AND MIXING CONCRETE.

All mixtures herein reported are by dry volume. Mixtures are referred to as one volume of cement to a given number of volumes of mixed aggregate. No distinction is made between what are generally termed mortar and concrete mixtures.

The weight of cement was assumed as 94 lb. per cu. ft.

The weight per cubic foot of the aggregate was determined by measuring in a machined cast-iron measure having a capacity of $\frac{1}{5}$ cu. ft. and the inside diameter equal to the depth. The test was made by filling the measure about $\frac{1}{3}$ full and puddling with a $\frac{5}{8}$-in. round steel bar pointed at the lower end. Filling and puddling were continued in like manner until the measure was full. After striking off with a straight edge, the weight was determined. This is the method recommended by Committee C-9 on Concrete and Concrete Aggregates of this Society, but it has not been standardized.

The hand-mixed concrete was mixed in the manner regularly followed for making such tests in this Laboratory. Each specimen was made from a batch of about $\frac{1}{5}$ cu. ft., which was proportioned separately and mixed with a bricklayer's trowel in a shallow metal pan. The machine-mixed concrete was mixed in a $3\frac{1}{2}$-cu-ft. Smith "Mascot" mixer.

The amount of mixing water is expressed as the ratio of volume of water to volume of cement. This so-called "water-ratio" has been shown by Abrams[1] to be the best criterion of the strength of concrete.

The term "consistency" is used to denote the plasticity of the concrete. This value is relative and does not indicate the actual amount of mixing water. The consistency called normal (relative consistency, 1.00) is of such a plasticity that a 6 by 12-in. concrete cylinder of ordinary mixtures will slump $\frac{1}{2}$ to 1 in. upon the removal of the metal form by a steady upward pull immediately after molding the specimen. An addition of 10 per cent of water (relative consistency, 1.10) will give a slump of 5 to 6 in. A relative consistency of 1.25 will cause a slump of about 8 to 9 in. The uniformity with which the slump can be determined varies considerably with the richness of the mix and nature of the aggregate.

TEST SPECIMENS.

Specimens were made in cylinder forms, 6 in. in diameter and 12 in. long, made of steel tubing. The concrete was puddled in a manner similar to that described above for determining unit weights of aggregates. The forms were placed on machined cast-iron base plates to insure a plane bearing surface for the bottom of the cylinder. Two or three hours after finishing a thin layer of neat cement paste, mixed before the cylinder was molded, was placed on the top of the specimen and a smooth surface formed by means of a glass plate. In general, the values for hand-mixed concrete are the average of five specimens made on different days. The values for machine-mixed concrete are the average of four specimens from different parts of the same batch.

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[1] D. A. Abrams, "Design of Concrete Mixtures," *Bulletin No. 1*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

In general, test specimens were stored in damp sand until the day of test.

COMPRESSION TESTS OF CONCRETE.

All specimens were tested in a 200,000-lb. Olsen universal testing machine. A spherical bearing block was used to obtain an even distribution of the load. In general deformation readings were taken at each 100 lb. per sq. in. increment up to 1000 lb. per sq. in., and at each 500 lb. per sq. in. thereafter until near failure. For the tests reported in Tables IV to XII, readings were taken with the head of the machine traveling about 0.01 in. per minute. For the later tests loads up to 50 to 75 per cent of the ultimate strength were applied with the head of the machine traveling about 0.05 in. per minute. For the higher loads the speed of 0.01 in. per minute was used. The machine was stopped at each increment of stress long enough to read the deformation accurately. A special investigation has shown that the rate of applying the load below 50 to 75 per cent of the ultimate has no effect on the strength.[1] The advantage of the latter method is that more tests can be made in a given time with no sacrifice of accuracy. Deformations were measured over a 6-in. gage length for all tests except those reported in Table XII.

EXTENSOMETERS USED IN CONCRETE TESTS.

A detail drawing of the instrument used for most of the tests reported in this paper is given in Fig. 2. This instrument differs from those used in certain other laboratories in five essentials:

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[1] D. A. Abrams, "Effect of Rate of Application of Load on the Compressive Strength of Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 364 (1917).

1. The bottom yoke is attached to the specimen by three set screws. This design allows no movement of the yoke, thus stabilizing the instrument.

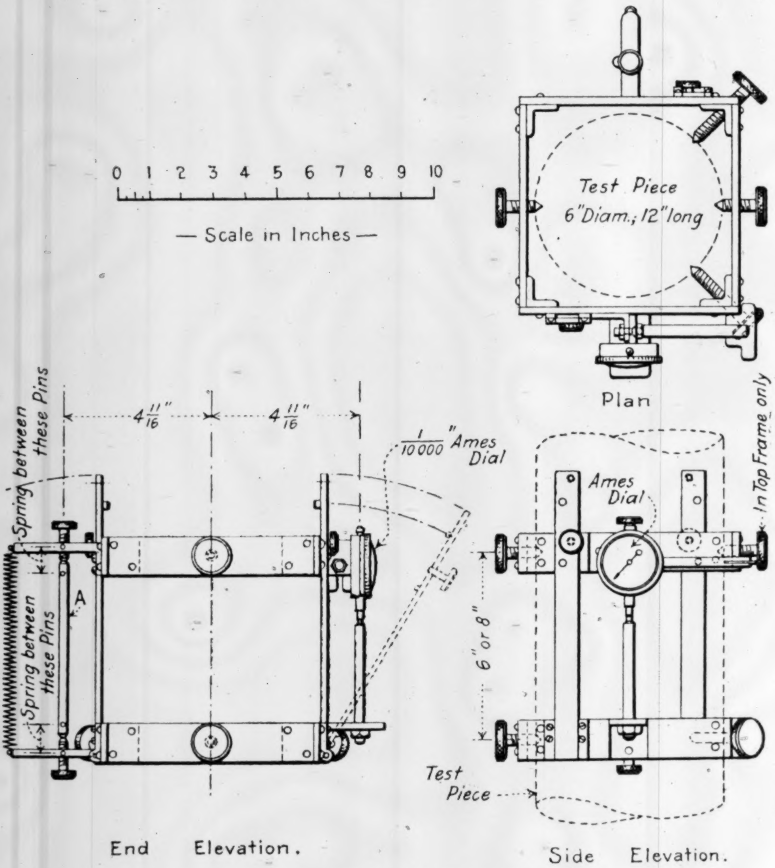
0 1 2 3 4 5 6 7 8 9 10
— Scale in Inches —
Test Piece
6"Diam.; 12" long
Plan
$4\frac{11}{16}$"
$4\frac{11}{16}$"
$\frac{1}{10000}$" Ames Dial
Spring between these Pins
A
Spring between these Pins
Ames Dial
In Top Frame only
6" or 8"
Test Piece
End Elevation.
Side Elevation.

FIG. 2.—Extensometer for Concrete Tests.

2. The deformation is measured by an Ames dial reading to 0.0001 in.

3. The average deformation of the cylinder is indicated on a single dial.

4. The dial can be readily removed before failure of the specimen.

5. The deformation is transmitted to the dial by means of a stiff steel rod.

The spacing bars shown in the plan are removed after the instrument is attached to the cylinder. The distance bar *A* maintains one side of the yokes in a fixed relation to each other. This arrangement causes the top yoke to rotate about its points of contact as the specimen is compressed. Twice the total deformation of the specimen is transmitted to the Ames dial. The dial is held in place by a self-seating wing nut.

This instrument was used on all tests except those reported under Series 89, about one-half of the tests for ages less than a year in Series 93, and on all tests at ages less than a year in Series 83.

The instrument used in the earlier tests had the same frame as that shown in Fig. 2 except that there were only two set screws in the bottom yoke. A Johnson wire-wound dial was used in the place of the Ames dial. The face of this instrument is divided in such a manner that direct readings of 0.001 in. can be taken, a vernier for reading 0.0001 in. being provided. The arc representing 0.001 in. deformation on the Johnson instrument is about equal to that representing 0.000025 in. deformation on the Ames. Aside from the difference in the divisions of the dial faces, the Johnson instrument is not as sensitive as the Ames. Movement of the indicator on the Johnson instrument is caused by a fine wire. There is always a certain amount of slack in the wire, and slip about the drum of the dial. This slack and slip is sometimes sufficient to cause a stress-deformation curve with an increasing slope, a relation which is not found in concrete and which is characteristic of only a few materials such as rubber.

STRESS-DEFORMATION RELATION.

There appears to be no general agreement among writers as to the form of the stress-deformation relation for concrete. Some writers are of the opinion that for the lower loads this is represented by a straight line; while most writers hold that there is a decreasing slope from the beginning.

A number of formulas have been offered as representing the relation between stress and deformation for concrete. The tests reported in this paper, and several thousands not included, indicate that this is of the form,

$$s = Kd^n \qquad (1)$$

where s = unit stress in the concrete, d = unit deformation of concrete, K = a constant depending on the strength of the concrete, and n = an exponent, approximately constant.

TABLE III.—STRESS-DEFORMATION RELATION FOR CONCRETE.

(Data from Series 120.)

Compression tests of 6 by 12-in. cylinders.
For details of tests see Fig. 3.

Stress, lb. per sq. in.	Unit Deformation, inches per inch.									
	190 C		187 C		188 C		221 C		224 C	
	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.	Exepri-mental.	Calculated.	Experimental.	Calculated.
0....	0	0	0	0	0	0	0	0	0	0
100....	0.00001	0.00001	0.00001	0.00001	0.00002	0.00001	0.00003	0.00003	0.00002	0.00002
200....	2	3	2	2	2	3	6	7	8	8
300....	5	5	4	4	5	5	11	11	12	12
400....	6	7	5	6	6	7	16	16	17	17
500....	10	10	8	8	9	9	21	21	22	24
600....	12	12	10	10	12	12	26	26	31	31
700....	13	14	12	12	13	14	31	31	40	38
800....	18	17	13	14	14	16	38	38	47	46
900....	21	20	16	16	18	18	42	43	60	54
1000....	22	22	18	18	22	21	49	49	75	63
1500....	38	36	31	30	34	34	88	83	....	....
2000....	52	52	43	43	48	48	....	....	....	....
2500....	68	68	55	55	62	63	....	....	....	....
3000....	79	84	68	68	74	76	....	....	....	....
3500....	95	102	87	83	88	91	....	....	....	....
4000....	....	....	172	96	104	107	....	....	....	....
4500....	....	....	....	....	121	123	....	....	....	....
5000....	....	....	....	....	142	141	....	....	....	....
Ultimate Strength, lb. per sq. in.......	4 200		4 010		5 210		1 890		1 060	
Value of n	0.824		0.810		0.844		0.812		0.715	
Value of K, lb. per sq. in....	1 030 000		1 040 000		1 260 000		478 000		196 000	

Bach gives a similar law. Mörsch[1] says, "The deformation curves found by Bach are so regular that they may be represented by an exponential equation, the relation between compression and stress being such that"

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[1] E. P. Goodrich, "Concrete-Steel Construction" (Translation of Mörsch's "Der Eisenbetonbau").

$$d = as^{r} \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where d = unit deformation of concrete, a = a constant, s = unit stress in concrete, and r = an exponent.

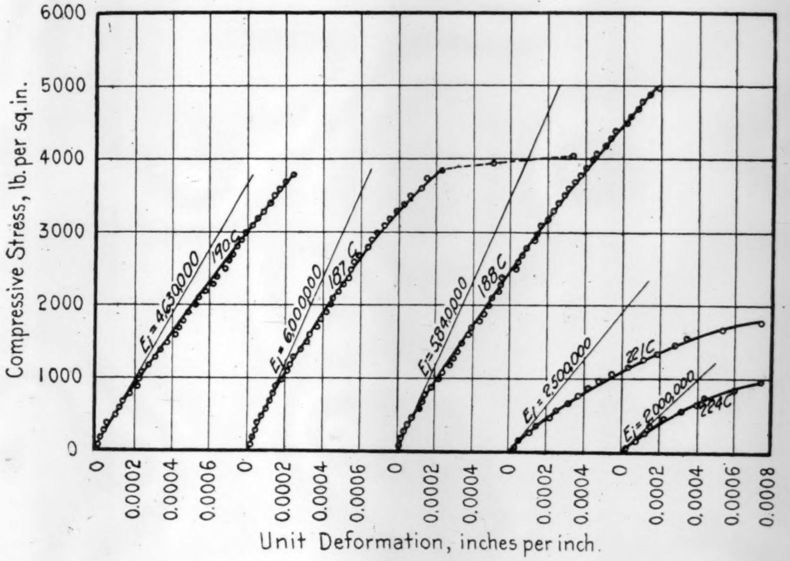

FIG. 3.—Typical Stress-Deformation Curves for Concrete.

Data from Table III.
Compression tests of 6 by 12-in cylinders.
Sand and pebble aggregate.
Gage length 6 in.

The following table gives details of the tests.

Ref. No.	Age at Test.	Mix.	Size of Aggregate.	Relative Consistency.	Compressive Strength, lb. per sq. in.
187-c	3 mo.	1:4	0-1½	0.90	4010
188-c	3 mo.	1:4	0-1½	1.00	5210
190-c	3 mo.	1:4	0-1½	1.25	4200
221-c	3 mo.	1:4	0-8	1.10	1890
224-c	3 mo.	1:4	0-8	1.10	1060

Eq. 2 is of the same nature as Eq. 1 and can readily be converted to the same form.

Fig. 3 gives typical stress-deformation diagrams from concrete tests made in this Laboratory. It is known from mathematical considerations that an equation of the form of Eqs. 1 or 2 will give a straight line when platted on logarithmic coordinates. Fig. 4 gives the same data shown in Fig. 3, except that stresses and deformations are platted to logarithmic scales. All of the curves give straight lines, thus showing that they may be represented by the form given in Eqs. 1 and 2 within the range of loads practical to measure and below stresses of 50 to 90 per cent of the compressive strength. In general the exact location of the point where this law no longer holds was not definitely determined. Its determination was not considered of sufficient importance to justify the additional expense. It seems probable that this point is approximately the same as the "yield point" mentioned by certain writers. The determination of "yield point" is discussed in detail below.

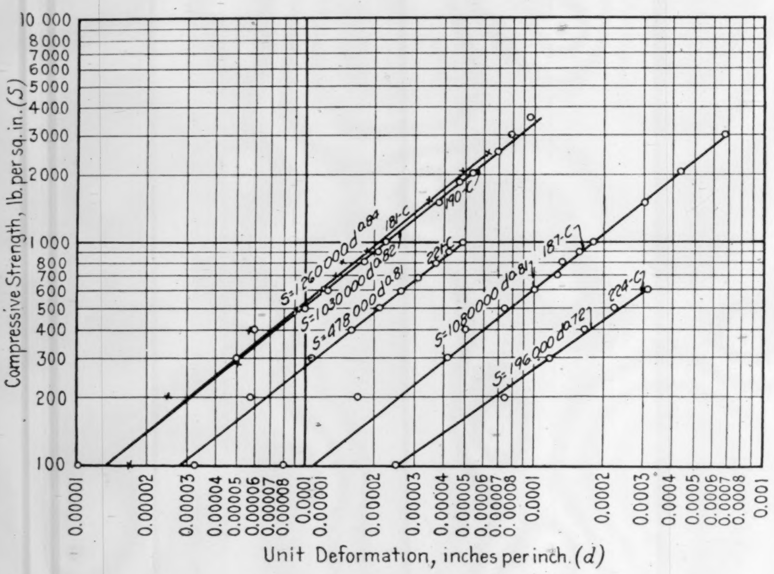

FIG. 4.—Typical Stress-Deformation Curves for Concrete. Same data as in Fig. 3, platted to logarithmic scales.

For the data given in Figs. 3 and 4 measurements were taken at shorter intervals for the higher loads than is our custom, for the purpose of showing more definitely the range over which the law given in Eq. 1 holds. The values of initial tangent modulus given in Fig. 3 should not be taken as necessarily typical for the concrete used, since only one specimen is represented in each curve.

Table III illustrates the manner in which the deformations for typical concrete as caluclated by Eq. 1 compare with the measured deformations. The data for this table are from the same tests as those given in Figs. 3 and 4. Having determined the constants required for Eq. 1 the unit deformations were calculated for the stresses shown. The calculated values agree with those determined in the test.

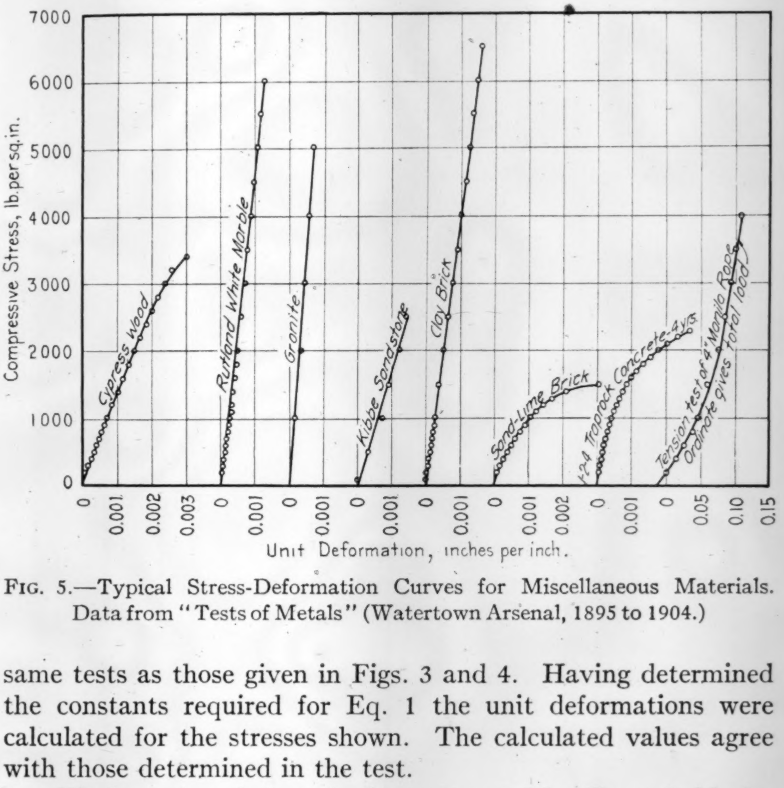

FIG. 5.—Typical Stress-Deformation Curves for Miscellaneous Materials. Data from "Tests of Metals" (Watertown Arsenal, 1895 to 1904.)

We have found that the law expressed by Eq. 1 holds for other materials as well as for concrete. Figs. 5 and 6 show stress-deformation curves for several materials, platted from data found in "Tests of Metals" (Watertown Arsenal, 1895 to

1904). Figs. 7 and 8 show the same curves platted to logarithmic scales. The curves platted in this form give straight lines, consequently they may be expressed by a function of the type of Eq. 1. Data from numerous other tests were platted and found to follow the same law. These tests included various woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds. An unsuccessful search has been made for stress-deformation data from either compression or tension tests that do not follow this law. It would appear, therefore, that the law stated above is general for all materials. Bach showed that this equation held for certain materials other than concrete.

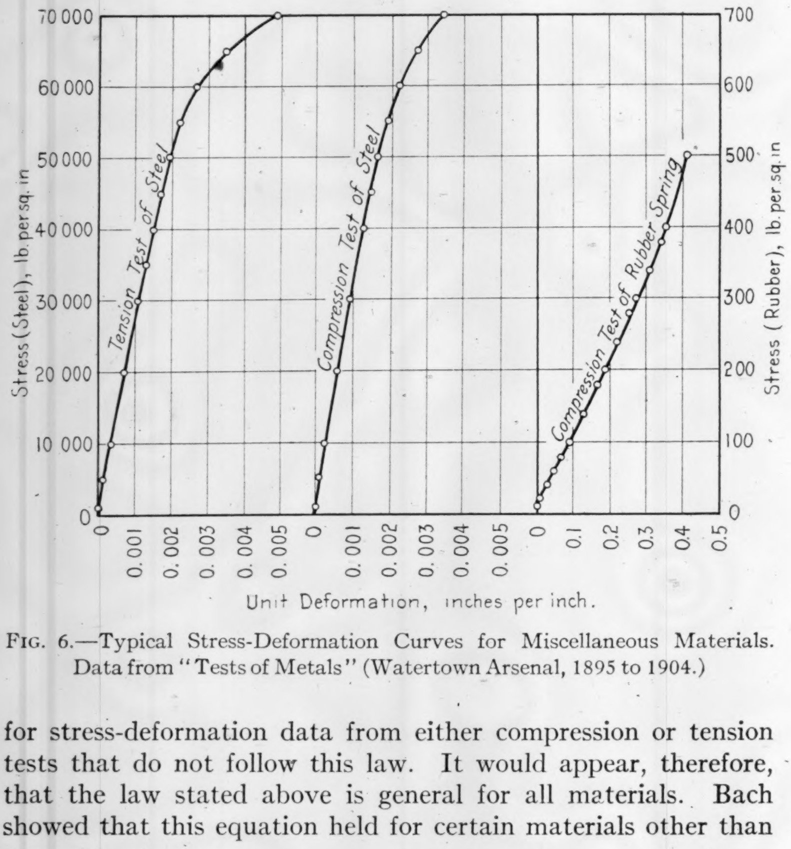

FIG. 6.—Typical Stress-Deformation Curves for Miscellaneous Materials. Data from "Tests of Metals" (Watertown Arsenal, 1895 to 1904.)

In studying data platted on logarithmic coordinates, it should be borne in mind that small discrepancies are apparently greatly exaggerated for the lower loads. On logarithmic coordinates the distance representing a change in deformation from 0.0001 in. to 0.0002 in. is the same as that representing a change of 0.01 in. to 0.02 in., etc.

Methods of Calculating Modulus of Elasticity.—The methods of calculating the secant and chord moduli are apparent. The secant modulus is the stress divided by the deformation at a given load. The chord modulus is the difference in stresses divided by the differences in deformations over the chosen increment.

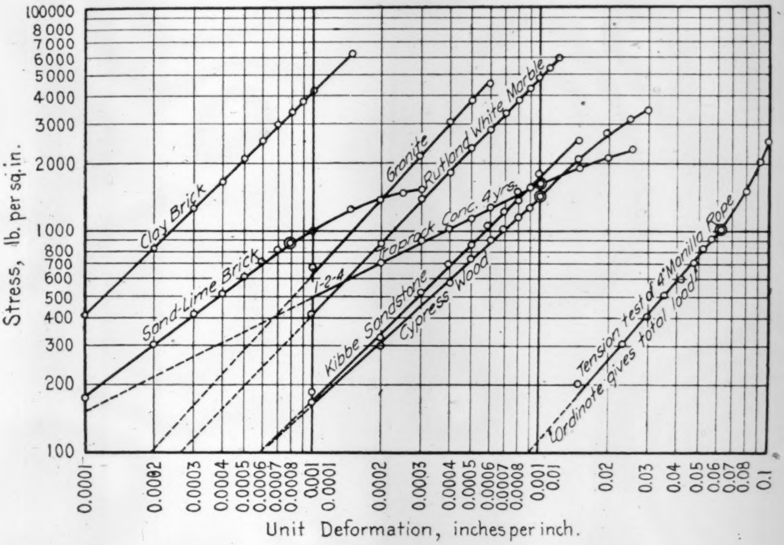

FIG. 7.—Typical Stress-Deformation Curves for Miscellaneous Materials. Same data as in Fig. 5, platted to logarithmic scales.

It is not so easy to arrive at the tangent modulus accurately unless the form of the curve is known. Investigation of the relation shown in Eq. 1 indicates that the true initial tangent modulus is infinity, if this equation holds to the origin of the curve. Instruments of sufficient delicacy are not available to determine this, but since this equation represents the relation for measurable loads below the point called the "yield point" it appears altogether reasonable to conclude that it holds for the very low loads. If the stress-deformation curve is platted to an exaggerated scale, and a smooth curve drawn to the origin, it will be found that this curve is of the form shown by Eq. 1.

The slope of the tangent at a given point on a curve is the first derivative of the function representing this curve. This gives from Eq. 1,

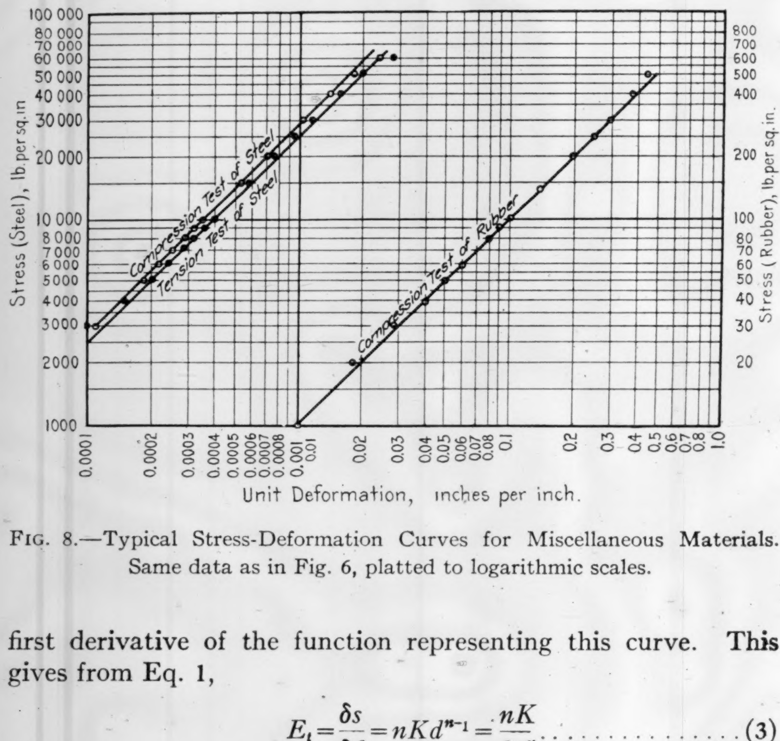

FIG. 8.—Typical Stress-Deformation Curves for Miscellaneous Materials. Same data as in Fig. 6, platted to logarithmic scales.

$$E_t = \frac{\delta s}{\delta d} = nKd^{n-1} = \frac{nK}{d^{1-n}} \qquad \text{.............. (3)}$$

Also,

$$\frac{s}{d} = \frac{Kd^n}{d} = \frac{K}{d^{1-n}} \qquad \text{...................... (4)}$$

Substituting in Eq. 3,

$$E_t = \frac{ns}{d} \qquad \text{.......................... (5)}$$

By definition,

$$E_s = \frac{s}{d} \qquad (6)$$

Therefore,

$$E_t = nE_s \qquad (7)$$

E_s can be obtained directly from the stress-deformation data. (See Eq. 6.) The most accurate method of determining n is to plat the stress-deformation curve to logarithmic scales. The logarithmic form is desirable since it affords a ready means of determining the average curve. It is much easier to draw a correct average line through points that are represented by a straight line than through points which fall on a curved line, the degree of curvature of which is not known. When platting the stress-deformation data on logarithmic coordinates, one must be sure that the instrument registered zero at zero load, or that the proper correction has been made. If care is not taken at this point the true relation will not be found. This Laboratory has found the use of the logarithmic coordinates most satisfactory in computing all modulus of elasticity data.

Determination of Constants.—Having platted the stress-deformation curve on logarithmic coordinates, it is easy to determine the constants K and n. It may be well to give a brief description of the working method.

The exponent n is the slope of the straight line, measured by the logarithms of the stresses and deformations. It may be calculated as the logarithm of the ratio of the stress at any deformation to the stress at one-tenth the first deformation. K is the stress at a unit deformation of 1, expressed in pounds per square inch. It may easiest be calculated as the anti-logarithm of the quantity $4n$ plus the logarithm of the stress at a unit deformation of 0.0001. For example on Fig. 4 the value of n for specimen No. 187 C may be calculated as the logarithm of the ratio of the stress at a unit deformation of 0.0002 to the stress at 0.00002. Then $n = \log. \frac{1080}{167} = 0.81$. For the same case $K = \text{anti-log.}\ (4 \times 0.81 + \log.\ 600) = 1{,}040{,}000$ lb. per sq. in.

It has been shown in Eq. 7 that n may be expressed as the ratio of tangent modulus to the secant modulus at the same load. In Figs. 9, 10 and 11 the secant modulus is platted against the tangent modulus. This relation is represented by a straight line passing through the origin. The slope of this line is the average value of *n*. These data are from Tables XII, XIII and XIV. This would indicate that for a given series of tests *n* is approximately constant. The relations shown in Figs. 9 and 11 are very uniform, while for Fig. 10 they are somewhat less

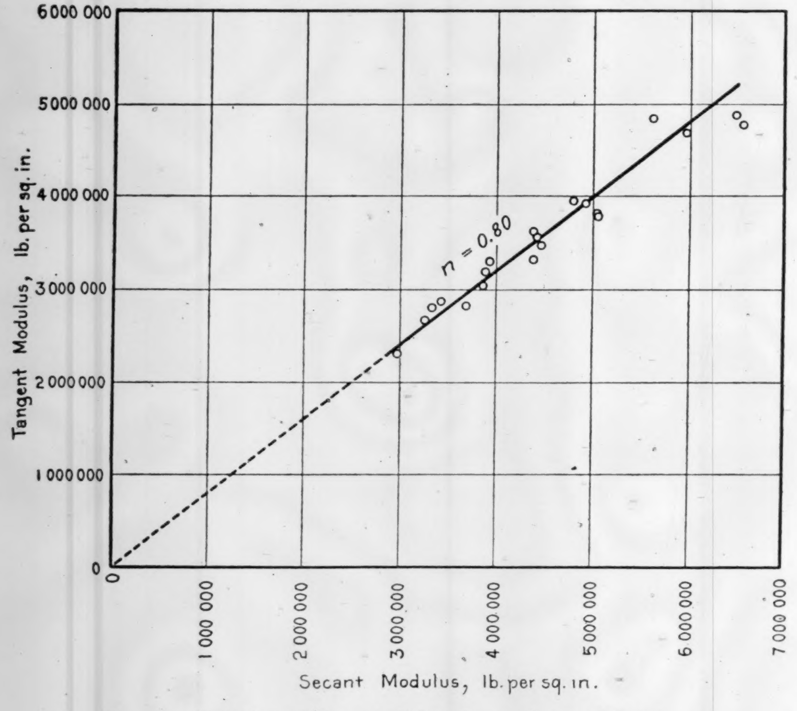

FIG. 9.—Relation of Tangent Modulus to Secant Modulus.

Average value of *n* for the tests in Table XII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Each value is the average of 80 tests, 20 each from 4 gage lengths.
Compare Figs. 10 and 11.

uniform. The graphically determined averages for *n* are 0.80, 0.90 and 0.92 for Figs. 9, 10 and 11, respectively.

K varies with the strength of the concrete and is greatly influenced by small changes in the value of *n*. Tables XII, XIII and XIV give values of *K* for concrete of different composition, age, etc. The values of *K* and *n* in the tables do not check exactly with the moduli of elasticity, due to the fact that average values of moduli of elasticity determined from the tests are reported, instead of moduli of elasticity from an average equation. It will readily be seen that the average constants of exponential equations do not give the same result as an average

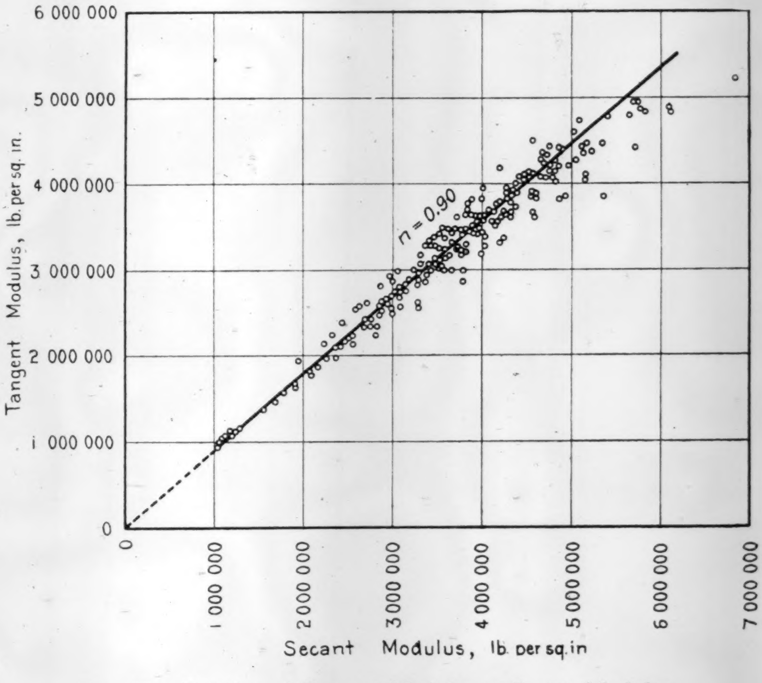

FIG. 10.—Relation of Tangent Modulus to Secant Modulus.

Average value of *n* for concrete in Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 9 and 11.

of the results of the individual equations. However, the difference is very small in a case, such as this, where the constants vary over a narrow range.

Nomographic Chart for Stress-Deformation Relation.—For material of a given composition under load, stress and deformation vary with a fixed relation to each other. Therefore, if the constants K and n are known and the stress is assumed, the corresponding unit deformation can be determined; or the unit stress can be calculated if the unit deformation is assumed. Fig. 12 gives a nomographic chart for solving Eq. 1. In the

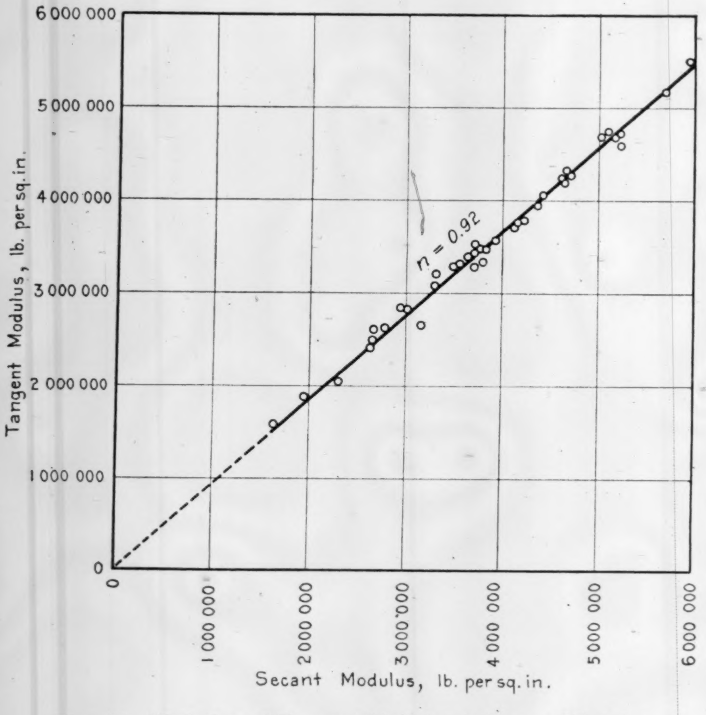

FIG. 11.—Relation of Tangent Modulus to Secant Modulus.

Average value of n for concrete in Table XIV.
7 and 28-day, and 3-mo. compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 9 and 10.

example worked out on the chart we assumed $K = 800{,}000$ lb. per sq. in. and $n = 0.75$. For these conditions concrete stressed to 800 lb. per sq. in. would have a unit deformation of 0.0001. (For a discussion of the principles of nomographic charts see "Graphical and Mechanical Computation," by Lipka.)

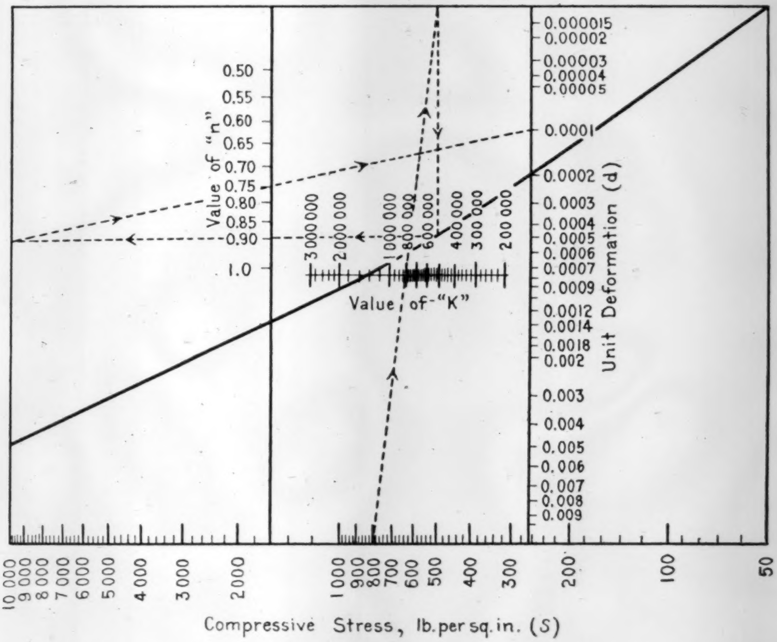

FIG. 12.—Nomographic Chart for Solving $s = Kd^n$.

DISCUSSION OF TESTS.

Tests are reported showing the effect of a number of different variables on the modulus of elasticity and strength of concrete.

Effect of Gage Length.—A series of tests was carried out for the purpose of discovering the influence of the gage length over which the deformations were measured on the modulus of elasticity of concrete when loaded in compression. This series included tests on concrete of 4 mixes: 1:7, 1:5, 1:4, and 1:3.

The aggregate was sand and pebbles, graded 0–1½ in. The concrete was of normal consistency (relative consistency, 1.00). Each set of tests consisted of 20 specimens made on different days. The details of these data are given in Table XII. Measurements were taken over gage lengths of 4, 6, 8 and 10 in. on 6 by 12-in. cylinders. In Fig. 13 the average of all of the mixes is platted to show the effect of gage length. The tests show that the gage length over which deformations were measured had no appreciable effect on the determination of modulus of elasticity. Since the gage length has no effect we are able to average all of the values obtained for each mix, thus securing moduli of elasticity and strengths which are the average of 80 tests.

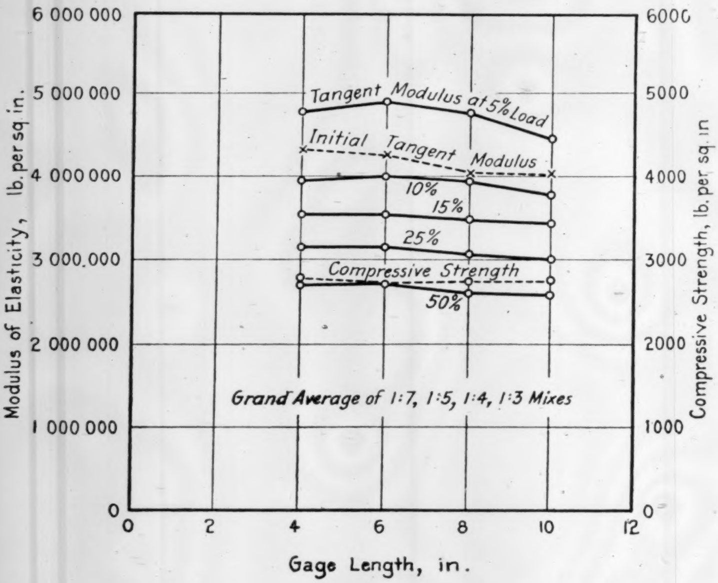

FIG. 13.—Effect of Gage Length on the Determination of Modulus of Elasticity.

Data from Table XII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–½ in.
Relative consistency 1.00.
Each value is the average of 80 tests, 20 each from 4 mixtures.

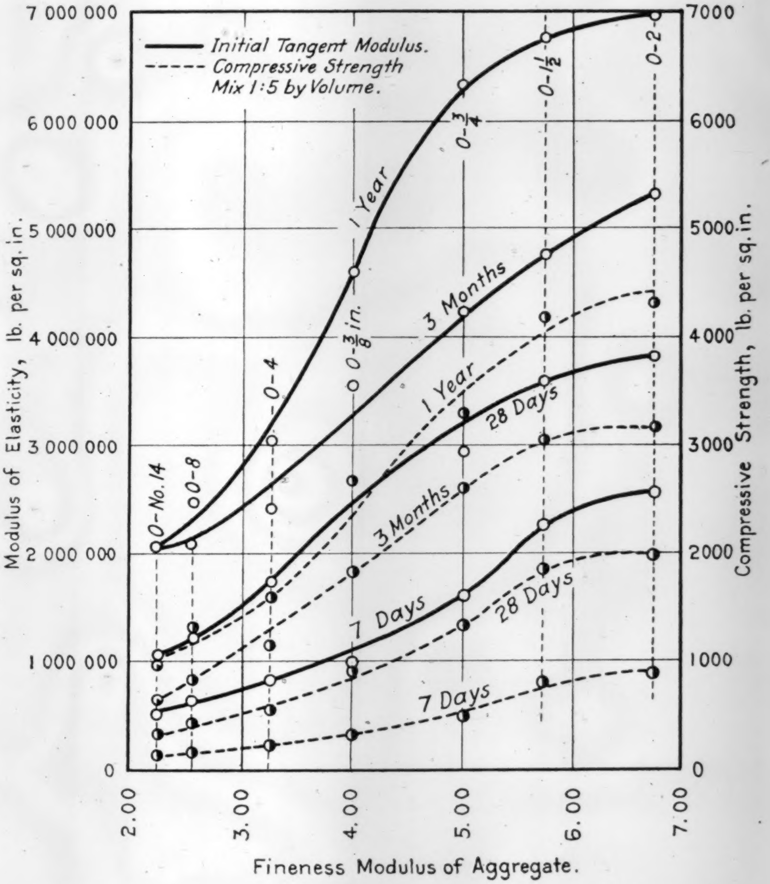

FIG. 14.—Effect of Size of Aggregate on Modulus of Elasticity.

Data from Table VII.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Figs. 15 and 16.

Effect of Grading of Aggregate.—In order to study a quantity intelligently one must have some numerical measure of it. Experimental work carried out in this Laboratory by Professor Abrams has given rise to what has been termed the fineness modulus[1] of the aggregate. This function is a measure of the size and grading. It may be defined as the sum of the percentages in the sieve analysis of the aggregate, divided by 100. The size of sieves used and the method of recording the sieve analysis are given in Table II. It has been shown that the fineness modulus may be used as a measure of the quantity of water necessary to produce concrete of a given plasticity using aggregates of different sizes and gradings.

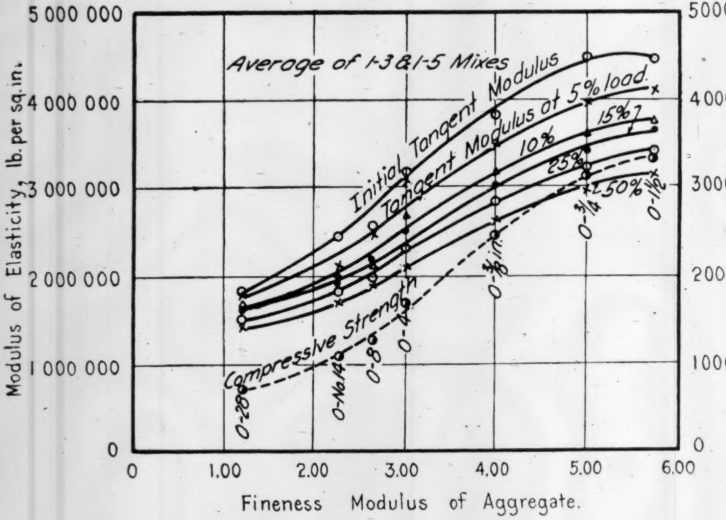

FIG. 15.—Effect of Size of Aggregate on Modulus of Elasticity.

Data from Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.00.
Each value is the average of 10 tests from 2 mixtures.
Compare Figs. 14 and 16.

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[1] For a discussion of this function, see "Design of Concrete Mixtures" by Duff A. Abrams. *Bulletin No. 1*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

Figs. 14 to 16, inclusive, show the effect of size and grading of aggregate on the modulus of elasticity and strength of concrete of various mixtures, ages, etc.

Fig. 14 shows the effect of size of aggregate on the strength and initial tangent modulus for a 1:5 mix and 1.10 consistency. The details of the tests are given in Table VII. The importance of a well-graded aggregate is apparent from these curves. For example, for the 28-day tests the strength obtained from an ordinary torpedo sand is about 500 lb. per sq. in., while that obtained from the 0–1½-in. aggregate is 1800 lb. per sq. in., an increase of 260 per cent. For the same conditions the moduli of elasticity are 1,800,000 and 3,600,000 lb. per sq. in. respec-

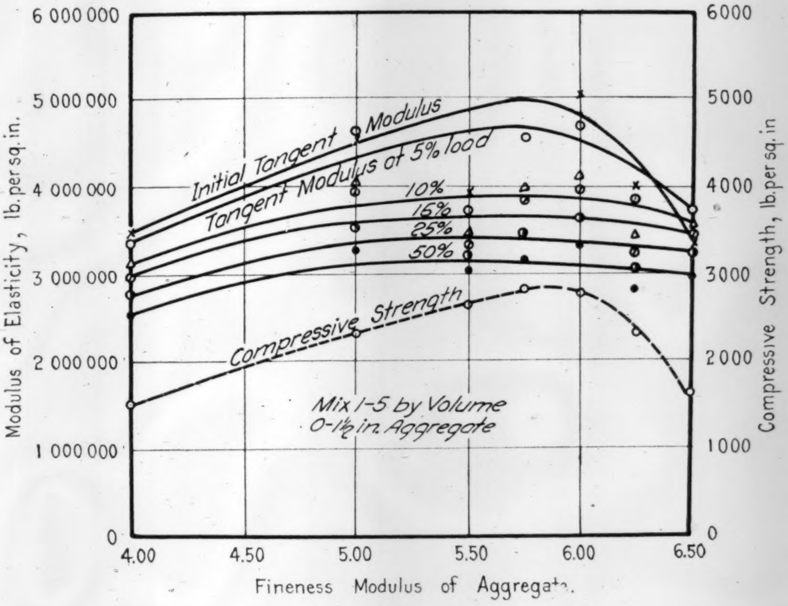

FIG. 16.—Effect of Grading of Aggregate on Modulus of Elasticity.

Data from Table XIII.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–½ in.
Relative consistency 1.00.
Compare Figs. 14 and 15.

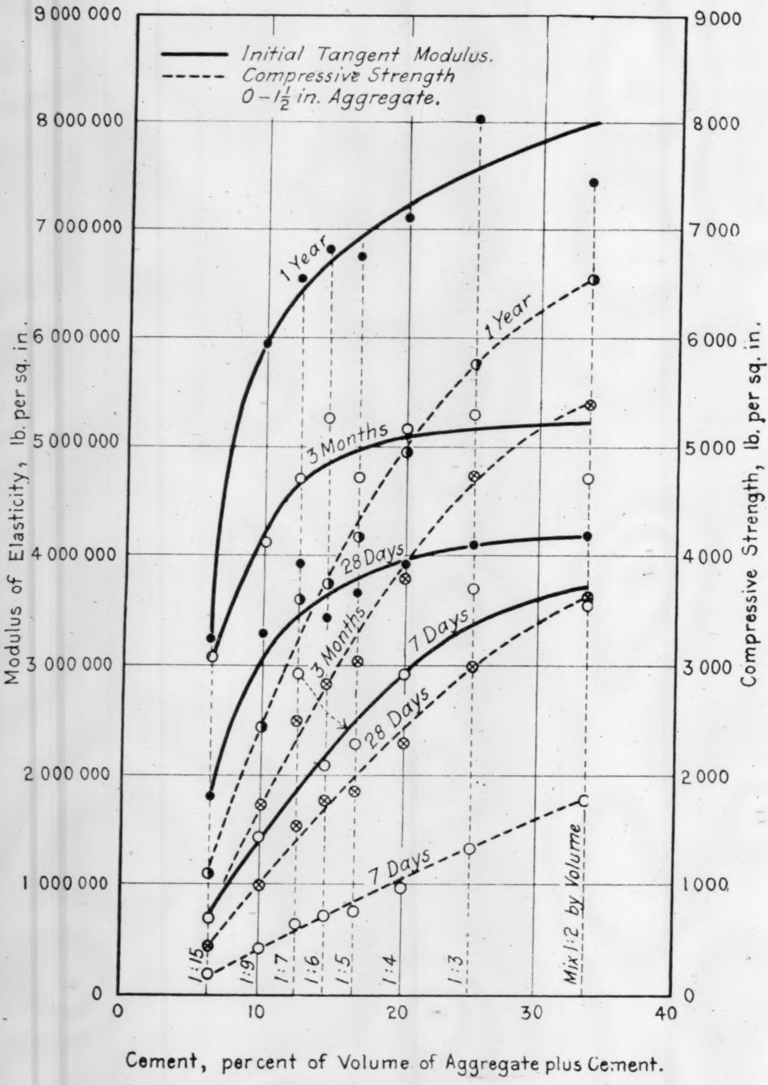

FIG. 17.—Effect of Amount of Cement on Modulus of Elasticity.

Data from Table VII. Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 18.

tively, or an increase of 100 per cent. The values from these tests are low, probably due to the fact that the specimens were made during the winter and stored in the basement where the temperature was somewhat low.

Fig. 15 gives additional data on the effect of size of aggregate on the modulus of elasticity at various percentages of the compressive strength for the average of the 1:3 and 1:5 mixes in Groups 1 and 2 of Table XIII.

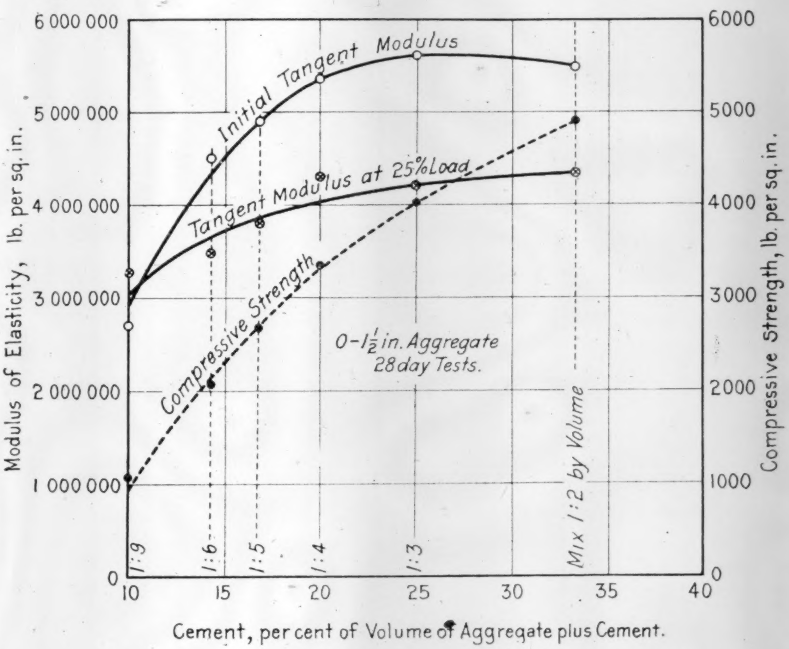

FIG. 18.—Effect of Amount of Cement on Modulus of Elasticity.

Data from Table XIV.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Compare Fig. 17.

Fig. 16 shows the effect of varying the proportions of fine and coarse aggregate, for a 1:5 mix and relative consistency of 1.00. The relation is shown for the strength, "initial tangent" modulus, and "tangent" modulus at stresses varying from 5 to 50 per cent of the compressive strength. These data illustrate the importance of combining the fine and coarse aggregate in the proper proportions.

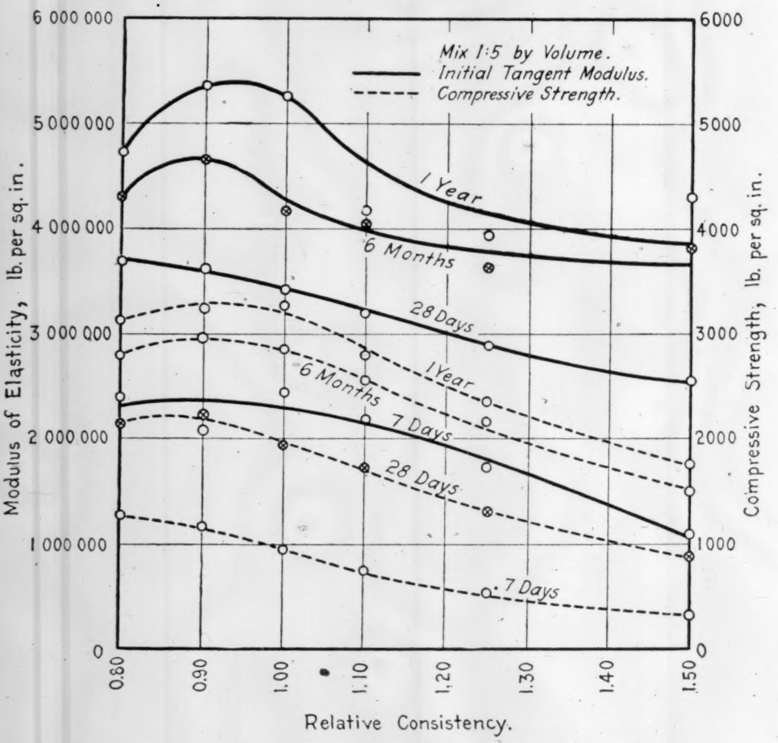

FIG. 19.—Effect of Consistency of Concrete on Modulus of Elasticity.

Data from Table IV.
Compression tests of 6 by 12-in. cylinders.
Each value is the average of 15 tests from 3 sizes of sand and pebble aggregate.
Compare Fig. 20.

All of these curves show that both the modulus of elasticity and strength are greater for the coarser aggregates — higher fineness moduli — up to a certain point beyond which this relation does not hold.[1] Similar relations are found for data given in Tables IV, VIII, XI and XIV. It will be noted that for each of the instances cited above, the modulus of elasticity increases less rapidly than the strength. It will be shown below that the other variables which affect the strength of concrete give a similar relation.

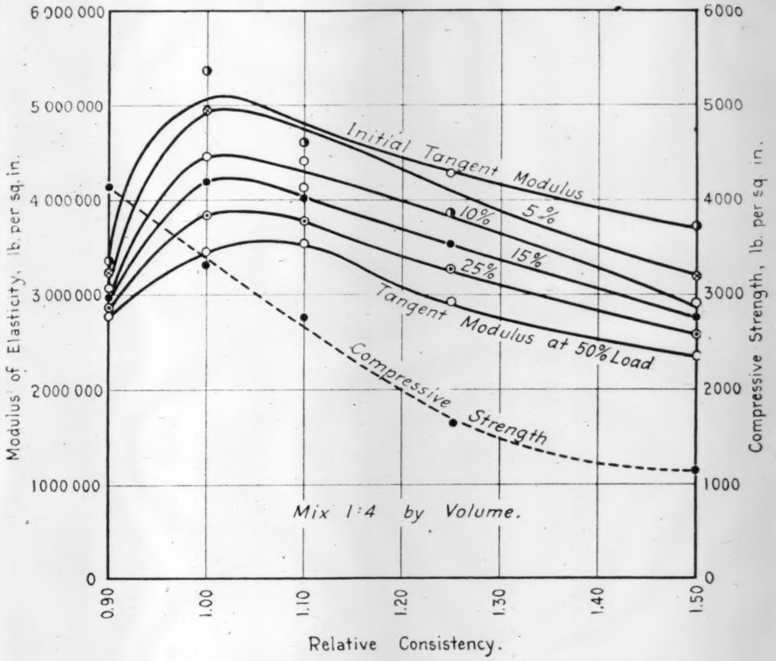

FIG. 20.—Effect of Consistency of Concrete on Modulus of Elasticity.

Data from Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Compare Fig. 19.

Effect of the Quantity of Cement.—Figs. 17 and 18 show the effect of the quantity of cement (the mix) on the strength and modulus of elasticity of concrete. The abscissas are quantities of the cement expressed as percentages of the sums of the

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[1] For definite information as to the maximum values of fineness modulus permissible to use for a given mix and maximum size of aggregate, see *Bulletin No. 1* referred to above.

TABLE IV.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Size of Aggregate, Age; Series 83.)

Compression tests of 6 by 12-in. cylinders.
Hand-mixed concrete.
Mix 1:5 by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; limestone from Chicago.
In general, each value is the average of 5 tests made on different days.
The 1-year Modulus of Elasticity values are the average of 2 or 3 tests.

Aggregate.		Water.		Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.			
Size.	Fineness Modulus.	Relative Consistency.	Water Ratio.	7d.	28d	6mo.	1yr.	7d.	28d	6mo.	1yr.
SAND AND PEBBLES.											
0–1½	6.00	0.80	0.66	2230	3250	3870	4430	2750	4250	5820	......
		0.90	0.74	2020	3560	4240	4580	2730	4920	6160	6200
		1.00	0.82	1660	3150	4370	4880	3350	4300	4860	6000
		1.10	0.91	1260	2720	3770	4370	2640	4020	5520	4100
		1.25	1.03	900	2220	3210	3330	2970	3940	4600	4600
		1.50	1.24	520	1340	2080	2290	......	3300	4820	6800
Average.				1430	2710	3590	3980	2890	4120	5300	5540
0–¾	4.50	0.70	0.74	1060	1890	2460	2780	2670	3140	4040	4350
		0.80	0.85	1070	2140	2820	3110	2780	3590	3760	5950
		0.90	0.95	990	2020	2930	3120	2310	3150	4040	5550
		1.00	1.06	790	1700	2730	2910	2660	3550	4000	6200
		1.10	1.17	630	1530	2490	2530	2420	3850	3980	5000
		1.25	1.33	470	1140	2030	2250	1350	2820	3920	3800
		1.50	1.60	330	880	1510	1870	1410	2670	4120	3350
Average.				760	1620	2420	2650	2230	3250	3980	4890
0–4	3.10	0.70	0.89	580	1060	1710	1830	1420	2730	3760	4850
		0.80	1.02	530	1090	1740	1810	1610	3350	3440	3570
		0.90	1.15	510	1120	1770	2030	1200	2840	3820	4400
		1.00	1.28	420	990	1500	1940	1250	2400	3720	3550
		1.10	1.40	350	810	1380	1520	1470	2020	2740	3370
		1.25	1.60	260	580	1240	1470	810	1900	2380	3330
		1.50	1.92	180	490	910	1120	740	1550	2460	2670
Average.				400	880	1460	1670	1210	2400	3190	3680
SAND AND CRUSHED LIMESTONE.											
0–1½	5.50	0.70	0.63	1280	1970	2490	2740	2820	3190	4080	4370
		0.80	0.72	1350	2500	3350	3540	2500	3810	4520	6030
		0.90	0.81	1590	2650	3820	3630	5340	4100	5380	5600
		1.00	0.90	1360	2720	3480	4540	3270	4300	5320	5830
		1.10	0.99	1100	2410	3820	4330	3600	4950	5080	5930
		1.25	1.13	730	1610	3040	3290	2470	4130	5760	4830
		1.50	1.35	420	1010	1710	2040	1220	3100	4600	4330
Average.				1120	2120	3100	3440	3030	3940	4960	5260

volumes of mixed aggregate plus cement. For example, in a 1:4 mix the quantity of cement is 20 per cent.

Fig. 17 shows the effect of quantity of cement on concrete made with 0–1½-in. aggregate, relative consistency of 1.10, and ages varying from 7 days to 1 year. For the 28-day tests the strength of a 1:7 mix is 1400 lb. per sq. in., while for a 1:3 mix it is 3000 lb. per sq. in.; or an increase of 111 per cent. For the same conditions the moduli of elasticity are 3,400,000 and 4,100,000 lb. per sq. in.; an increase of 21 per cent. The details of the tests are given in Table VII. The values are low, probably due to the fact that the specimens were made in the winter and stored in the basement where the temperature was somewhat low. A similar relation is shown for initial tangent modulus and tangent modulus at 25 per cent of the compressive strength from another series of tests in Fig. 18. Details are given in Table XIV.

TABLE V.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Age; Series 89.)[1]

Compression tests of 6 by 12-in. concrete cylinders.
Machine-mixed concrete.
Mix 1:4 by volume.
Stored in damp sand, tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1¼ in.
Each value is the average of 24 tests from 6 mixing times from ¼ to 10 min.

Water.		Compressive Strength, lb. per sq. in.			Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.		
Relative Consistency.	Water Ratio.	7 days.	28 days.	2 mo.	7 days.	28 days.	2 mo.
0.90	0.66	1870	3480	4070	3400	5440	5630
1.00	0.72	1390	2710	3470	3790	3990	5220
1.10	0.80	1200	2460	3170	3010	4480	4560
1.25	0.91	960	1850	2570	2680	3360	4590
1.50	1.08	510	1080	1660	1740	4260	3850
2.00	1.45	190	560	920	....	3020	3480
Average..................		1020	2020	2640	2920	4090	4560

Tables VIII, IX, X, XII and XIII give additional tests showing the effect of quantity of cement. These data show that both the modulus of elasticity and strength become greater as the quantity of cement is increased. It will be noted that for mixes richer than about 1:3, there is a marked falling-off in the rate of increase of the modulus of elasticity.

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[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete." D. A. Abrams, *Proceedings*, Am. Concrete Inst., 1918.

Effect of Consistency.—Figs. 19 and 20 show the effect of quantity of mixing water on the strength and modulus of elasticity of concrete. The abscissas are the relative amounts rather than the actual quantities of water. The details of the tests are given in Tables IV and XIII. A relative consistency of 1.00 gives a mix of such plasticity that if the steel form is withdrawn from a freshly molded 6 by 12-in. cylinder, the concrete will slump $\frac{1}{2}$ to 1 in. Concrete of this plasticity is somewhat drier than that used in ordinary reinforced concrete work.

TABLE VI.—MODULUS OF ELASTICITY OF CONCRETE.

(Time of Machine Mixing.)

Compression tests of 6 by 12-in. concrete cylinders.
Stored in damp sand; tested damp.
Aggregate: Sand and pebbles from Elgin, Ill.; graded 0–1$\frac{1}{2}$ in.
For Series 89, each value is the average of 24 tests from 6 consistencies, for a 1:4 mix;
For Series 93, each value is the average of 60 tests from 8 mixes and 7 gradings.

Time of Mixing, min	Compressive Strength, lb. per sq. in.					Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.				
	7d.	28d.	2mo.	3mo.	1yr.	7d.	28d.	2mo.	3mo.	1yr.
(DATA FROM SERIES 89.)[1]										
10......	1450	2570	3210	....	....	3090	4180	4700	....	....
5......	1280	2470	3040	....	....	3090	4490	4550	....	....
2......	1010	2020	2670	....	....	2970	4400	3960	....	....
1......	1010	2140	2760	....	....	2750	4390	4840	....	....
$\frac{1}{2}$......	840	1820	2500	....	....	3010	4080	4990	....	....
$\frac{1}{4}$......	790	1610	2230	....	....	2340	3320	4210	....	....
Average.	1060	2100	2740	....	....	2880	4140	4540	....	....
(DATA FROM SERIES 93.)[1]										
10......	1010	1860	....	2800	3760	2290	3380	....	5740	....
5......	830	1750	....	2880	3740	2330	3610	....	4490	6350
2......	650	1540	....	2630	3440	1840	2950	....	4240	5960
1......	480	1440	....	2450	3340	1890	2750	....	3460	5480
$\frac{1}{2}$......	430	1200	....	2200	2950	1470	2630	....	3460	4990
$\frac{1}{4}$......	380	1080	....	1950	2640	1530	2410	....	3550	4870
Average.	630	1480	....	2480	3310	1890	2960	....	4160	5530

[1] For details see D. A. Abrams, *loc cit.*

For the 28-day tests in Fig. 19 an addition of 25 per cent of water to the concrete having a relative consistency of 1.00 causes a decrease in strength of about 35 per cent, and a decrease in modulus of elasticity of about 15 per cent. Additional data from another series of tests are given in Fig. 20.

TABLE VII.—MODULUS OF ELASTICITY OF CONCRETE.

(Quantity of Cement, Size of Aggregate, Age; Series 93.)[1]

Compression tests of 6 by 12-in. cylinders.
Machine-mixed concrete.
Mix by volume.
Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Stored in damp sand; tested damp.
Each value is the average of 24 tests from 6 mixing times from ¼ to 10 min.

Mix by Vol.	Aggregate.		Water Ratio.	Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.			
	Size.	F. M.		7d.	28d.	3mo.	1yr.	7d.	28d.	3mo.	1yr.
QUANTITY OF CEMENT.											
1:2.....	0–1½	5.75	0.60	1760	3600	5380	6540	3620	4170	4720	7440
1:3.....	....	....	0.70	1310	2990	4720	5740	3700	4050	5320	8070
1:4.....	....	....	0.81	960	2270	3780	4950	2930	3880	5160	7160
1:5.....	....	....	0.91	760	1830	3030	4170	2250	3680	4740	6750
1:6.....	....	....	1.01	700	1740	2820	3740	2030	3420	5300	6870
1:7.....	....	....	1.10	640	1520	2490	3580	2940	3940	4730	6560
1:9.....	....	....	1.32	390	950	1710	2420	1380	3290	4160	5930
1:15....	....	....	1.94	180	410	710	1090	720	1800	3060	3220
Average..........				840	1910	3080	4030	2450	3530	4650	6500
SIZE OF AGGREGATE.											
1:5...	0–14	2.30	1.57	120	310	640	980	460	1060	2000	2000
	0–8	2.80	1.51	160	410	830	1310	600	1220	2100	2430
	0–4	3.40	1.43	200	500	1100	1570	780	1700	2370	3060
	0–⅜	4.00	1.25	320	890	1830	2660	970	2430	3580	4660
	0–¾	5.00	1.08	470	1300	2600	3290	1610	2940	4240	6350
	0–1½	5.75	0.91	760	1830	3030	4170	2250	3680	4740	6750
	0–2	6.70	0.82	850	1990	3150	4300	2500	3800	5280	6940
Average..........				410	1030	1880	2610	1310	2400	3470	4600

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[1] For details see D. A. Abrams, *loc. cit.*

The amount of mixing water used has a most marked effect on the strength and modulus of elasticity of the resulting concrete. These tests as well as many others made in this Laboratory show that the benefits of well-graded aggregates and rich mixes may be minimized or lost by using too much mixing water.

It will be noted that abnormally low strengths and moduli are obtained for relative consistencies less than about 0.90 to 1.00. Such consistencies are too dry for proper mixing and molding.

It has been shown by Abrams[1] that the quantity of mixing water expressed as a ratio to the volume of cement dictates the strength of the resulting concrete, regardless of the mix, consistency, and grading of aggregate, so long as the concrete is plastic.

TABLE VIII.—MODULUS OF ELASTICITY OF CONCRETE.

(Quantity of Cement, Size of Aggregate, Age; Series 93.)[1]

Compression tests of 6 by 12-in. cylinders.
Hand-mixed concrete.
Mix by volume.
Relative consistency, 1.10.
Aggregate: Sand and pebbles from Elgin, Ill.
Stored in damp sand; tested damp.
Each value is the average of 4 tests made on different days.

Mix by Vol.	Aggregate.		Water Ratio.	Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.			
	Size.	F. M.		7d.	28d.	3mo.	1yr.	7d.	28d.	3mo.	1yr.
				QUANTITY OF CEMENT.							
1:2	0–1½	5.75	0.50	1560	3380	5060	6400	3500	3320	5820	4900
1:3	....	....	0.70	1300	2780	4200	6000	3050	3320	5400	6080
1:4	....	....	0.81	940	2180	3660	4600	2420	4000	5120	7220
1:5	....	....	0.91	760	1950	3480	4400	2350	2950	4950	7100
1:6	....	....	1.01	580	1670	3090	3800	1900	3750	5350	6880
1:7	....	....	1.10	530	1430	2550	3220	2020	2800	5600	6570
1:9	....	....	1.32	360	1030	1870	2450	2130	4100	4200	5350
1:15	....	....	1.94	190	440	800	1030	800	2270	2930	2870
Average				780	1860	3090	3990	2270	3310	4920	5870
				SIZE OF AGGREGATE.							
1:5	0–14	2.30	1.57	140	380	870	1350	380	1700	2530	2580
	0–8	2.80	1.51	160	500	950	1480	600	2230	2000	2680
	0–4	3.40	1.43	180	600	1310	1890	800	2070	2950	3430
	0–⅜	4.00	1.25	270	900	1720	2540	1170	1700	3600	5700
	0–¾	5.00	1.08	440	1260	2550	2960	2850	2520	4000	7850
	0–1½	5.75	0.91	760	1950	3480	4400	2350	2950	4950	7100
	0–2	6.70	0.82	670	2000	3500	4760	1800	3320	4800	6700
Average				370	1080	2060	2770	1420	2360	3550	5150

[1] For details see D. A. Abrams, *loc. cit.*

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[1] D. A. Abrams, "Effect of Time of Mixing on the Strength and Wear of Concrete," *Proceedings*, Am. Concrete Inst., June, 1918; also "Design of Concrete Mixtures," *Bulletin No. 1*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

Effect of Age of Concrete.—Figs. 21 and 22 show the effect of age on the modulus of elasticity and strength of concrete for ages ranging from 7 days to 1 year. The details of the tests are given in Tables IV and VII.

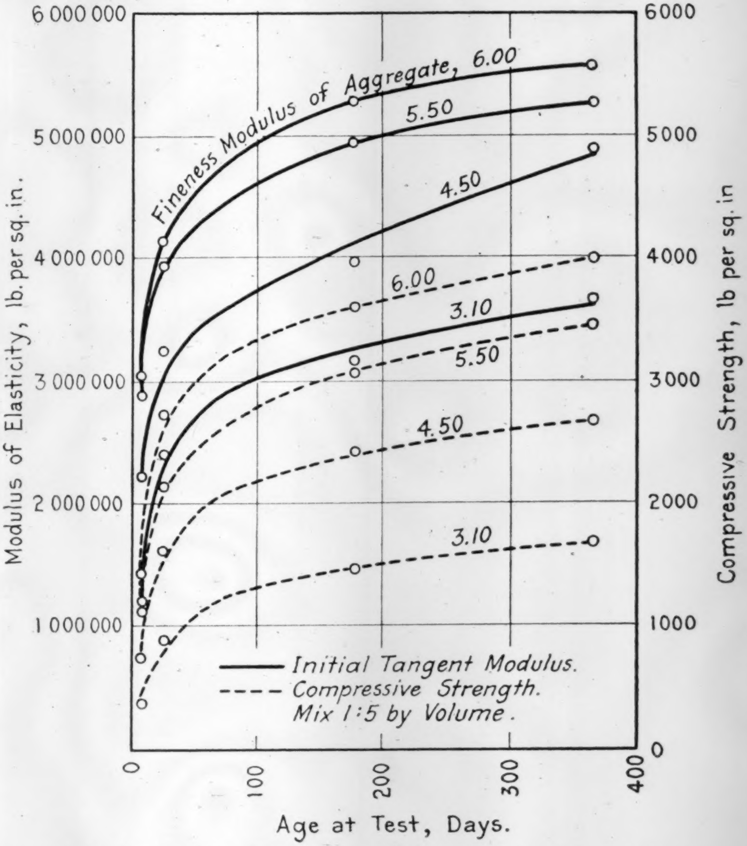

FIG. 21.—Effect of Age of Concrete on Modulus of Elasticity.

Data from Table IV.
Compression tests of 6 by 12-in. cylinders.
Mix 1:5 by volume.
Each value is the average of 30 to 35 tests from 6 or 7 consistencies.
Compare Fig. 22.

Fig. 21 shows the influence of age on modulus of elasticity and strength platted in the form of the usual age-strength curve. In Fig. 22 the age is platted to a logarithmic scale. On this

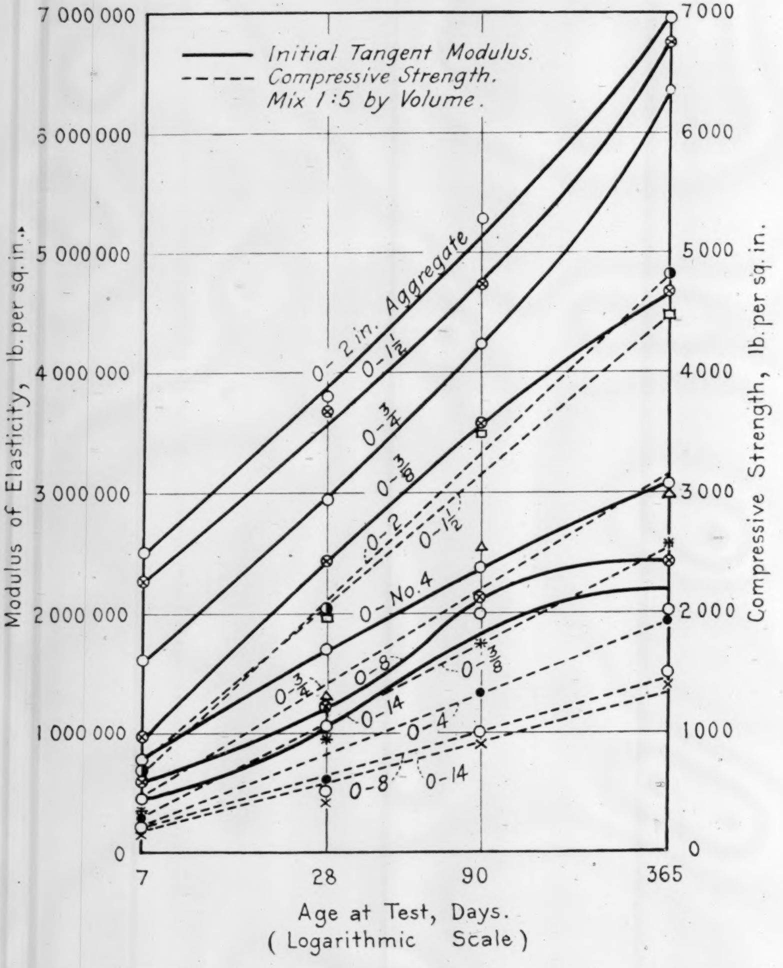

FIG. 22.—Effect of Age of Concrete on Modulus of Elasticity; Age Platted to Logarithmic Scale.

Data from Table VII.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 or 7 times of mixing.
Compare Fig. 21.

diagram it will be noted that the age-strength relation is a straight line. This indicates that the strength is proportional to the logarithm of the age.[1] The age-modulus-of-elasticity relation is also approximately a straight line. Here, as for the other variables, the modulus of elasticity does not increase as rapidly as the strength. For the 2-in. aggregate the modulus of elasticity at 1 year is 180 per cent of the value at 28 days, while the strength for 1 year is about 230 per cent of that at 28 days.

Effect of Kind of Aggregate.—In Table X moduli of elasticity and strengths are given for concrete made from four different coarse aggregates: crushed limestone, pebbles, crushed blast furnace slag and crushed granite. All coarse aggregates were similarly graded, the sizes ranging from No. 4 sieve to 1½ in. A high-grade torpedo sand was used as fine aggregate. Parallel tests were made on mixes from 1:6 to 1:2, of 1.10 consistency, for two conditions of storage: (1) 14 days in damp sand and 77 days in air, and (2) 3 months in damp sand. The following table gives average strengths and moduli of elasticity for all mixes and both conditions of storage:

Kind of Aggregate.	Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	
		Initial Tangent.	Tangent at 25 per cent of Compressive Strength.
Limestone	3 930	5 940 000	4 210 000
Pebbles	3 810	5 400 000	3 860 000
Slag	3 800	5 580 000	4 220 000
Granite	3 970	5 780 000	4 100 000

These tests show little variation in either strength or modulus of elasticity of concrete made from the four types of coarse aggregates. This result should be contrasted with the published tests on concrete made from different aggregates. These tests undoubtedly show the correct relation. The uniformity in properties is to be expected since the aggregates were graded alike and the water proportioned in such a manner that the varying absorption was taken into account. Many serious errors have been made in discussing tests of this kind due to failure to take into account differences in grading and absorption of aggregate.

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[1] D. A. Abrams, "Effect of Age on the Strength of Concrete," *Proceedings*, Am. Soc. Test. Mats., Part II, p. 317 (1918.)

Effect of Curing Condition of Concrete.—Table X gives tests on 140 6 by 12-in. cylinders, about half of which were stored 3 months in damp sand and the remainder 14 days in damp sand and 77 days in air. A grand average of the strength and modulus of elasticity for each condition of storage shows that the concrete stored the entire time in damp sand gives the higher values. The average compressive strength of air-stored specimens was 3640 lb. per sq. in. and for the sand-stored specimens 4100 lb. per sq. in. The average initial tangent modulus for

TABLE IX.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency—Age.)

Compression tests of 6 by 12-in. cylinders.
Machine-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1½ in.
For Series 96, each value is the average of 24 tests from 6 rates of rotation of mixer drum from 8 to 30 r.p.m.
For Series 97, each value is the average of 105 tests from 21 temperatures of mixing water from 0 to 100° C.

Water.		Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.		
Relative Consistency.	Water Ratio.	7d.	28d.	3mo.	1yr.	28d.	3mo.	1yr.
MIX 1:5—DATA FROM SERIES 96.[1]								
1.00	0.83	1120	2670	4160	5180	3290	5210	6070
1.10	0.91	720	2080	3220	4280	3790	4550	5730
1.10	0.91	740	1930	3300	4140	4190	5350	5280
1.10	0.91	830	2010	3080	4100	3850	5520	5720
1.25	1.04	560	1410	2770	3570	3380	4870	5230
1.50	1.21	360	970	1780	2660	3430	4240	4840
Average.....	....	720	1840	3050	3990	3660	4960	5480
MIX 1:4—DATA FROM SERIES 97.[1]								
0.90	0.68	1740	3440	4740	....	4300	5700	....
1.00	0.76	1370	3080	4380	....	3910	5350	....
1.10	0.83	1120	2720	4090	....	3740	5320	....
1.25	0.95	950	2160	3450	....	3470	4830	....
Average.....	....	1300	2850	4160	....	3860	5300	....

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[1] **For details see D. A. Abrams, *loc cit.***

TABLE X.—MODULUS OF ELASTICITY OF CONCRETE.

(Mix and Kind of Aggregate—Series 98.)

Compression tests of 6 by 12-in. cylinders.
Mix by volume.
Fine aggregate; 0–No. 4 sand from Elgin, Ill.
Coarse aggregate; No. 4–1½ in.
Relative Consistency 1.10.
Age at test 3 months.
Each value for air-stored specimens is the averge of 2 tests made on different days.
Each value for sand-stored specimens is the average of 3 tests made on different days.

Mix by Vol.	Water Ratio.	Stored in Sand 14 d., Air 77 d.					Stored in Sand 3 mo.					Average of all Conditions.
		Limestone.	Pebbles.	Slag.	Granite.	Average.	Limestone.	Pebbles.	Slag.	Granite.	Average.	
COMPRESSIVE STRENGTH, LB. PER SQ. IN.												
1:6	1.04	2120	2160	1790	2020	2020	2560	2690	2820	2440	2620	2320
1:5	0.92	2880	2890	2460	2340	2640	3550	3360	2970	3350	3310	2970
1:4½	0.87	3320	3040	2820	2870	3010	3660	3660	3590	3680	3640	3340
1:4	0.82	3250	3740	3620	3590	3550	4180	4110	3810	4390	4120	3840
1:3½	0.77	4510	3980	4100	4740	4330	4520	4400	4470	4080	4370	4350
1:3	0.71	4750	5060	4620	5230	4920	4870	4390	4660	5340	4820	4870
1:2	0.61	5140	4520	5440	4980	5020	5700	5320	6060	6160	5810	5420
Average..........		3710	3630	3550	3680	3640	4150	3990	4050	4260	4100	3870
"INITIAL TANGENT" MODULUS OF ELASTICITY, 1000 LB. PER SQ. IN.												
1:6	1.04	3500	4800	3500	5300	4280	5800	5000	4900	5230	5230	4750
1:5	0.92	5000	5700	4600	5500	5200	5900	5500	5430	7200	6010	5600
1:4½	0.87	4600	6200	5500	5400	5420	5900	5000	5500	6500	5720	5570
1:4	0.82	5800	4800	4100	5700	5100	7600	5900	6000	5700	6300	5700
1:3½	0.77	7500	4800	6700	4800	5950	6600	6200	6000	5600	6100	6020
1:3	0.71	6500	4800	5200	4800	5320	6200	5900	6900	6600	6400	5860
1:2	0.61	5700	4800	6700	7000	6050	6600	6200	7100	5500	6350	6200
Average..........		5510	5130	5190	5500	5330	6370	5670	5980	6050	6020	5670
TANGENT MODULUS OF ELASTICITY AT 25 PER CENT LOAD, 1000 LB. PER SQ. IN.												
1:6	1.04	2820	3780	3200	3270	3270	4520	4380	3780	3510	4050	3660
1:5	0.92	2870	3540	2890	3400	3180	4610	4720	4730	4940	4750	3970
1:4½	0.87	2920	4950	3370	3680	3730	4450	3980	4110	4740	4320	4030
1:4	0.82	3740	2880	2680	4860	3540	5890	4200	4720	3730	4640	4090
1:3½	0.77	5600	2770	5200	2900	4120	3500	4570	5540	4890	4620	4370
1:3	0.71	4500	3140	3730	4280	3910	4510	4040	5360	5300	4800	4360
1:2	0.61	3760	2910	3960	4500	3780	5250	4160	5780	3400	4650	4220
Average..........		3740	3420	3580	3840	3650	4680	4290	4860	4360	4550	4100

air-stored specimens was 5,330,000 and for the sand-stored specimens 6,020,000 lb. per sq. in. The tangent modulus at 25 per cent of the compressive strength was 3,650,000 for the air-stored concrete and 4,550,000 lb. per sq. in. for that stored in damp sand.[1]

Effect of Time of Mixing.—Table VI gives data on the effect of time of mixing on the strength and modulus of elasticity of concrete. The values given in this table are the average of a number of different consistencies, sizes of aggregates, and mixes. The details of the strength tests were reported by Professor Abrams to the American Concrete Institute in 1918.

TABLE XI.—MODULUS OF ELASTICITY OF CONCRETE.

(Grading and Size of Aggregate; Series 98.)

Compression tests of 6 by 12-in. cylinders.
Hand-mixed concrete.
Mix 1:4 by volume.
Relative consistency 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Average of specimens stored 14 days and 90 days in damp sand.
Age at test 3 months.
In general, each value is the average of 5 tests made on different days.

Size of Aggregate.	Fineness Modulus of Aggregate.	Water Ratio.	Compressive Strength, lb. per sq. in.	Initial Tangent Modulus, 1000 lb. per sq. in.	Tangent Modulus at 25 per cent Load, 1000 lb. per sq. in.
0–1½	4.00	1.04	2130	4570	3340
	5.00	0.92	3170	4840	3590
	5.50	0.88	3560	5440	3980
	5.75	0.85	3650	5530	4020
	6.00	0.82	3610	5360	3910
	6.25	0.80	3550	5320	3940
0–28	1.20	1.33	890	1900	1800
0–14	2.20	1.22	1380	2300	1920
0–8	2.65	1.18	1790	4300	2940
0–4	3.25	1.10	2230	4700	3580
0–⅜	4.50	0.98	3430	5400	4400
0–¾	5.40	0.89	3410	4600	3400
0–1¼	5.90	0.83	3650	5300	4470
0–1½	6.00	0.82	3560	5800	3900

In general both the modulus of elasticity and strength are greater for the longer mixing times.

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[1] For further information on the effect of curing conditions see "Effect of Curing Condition on the Wear and Strength of Concrete" by D. A. Abrams, *Bulletin No. 2*, Structural Materials Research Laboratory.

TABLE XII.—MODULUS OF ELASTICITY OF CONCRETE.

(Mix and Gage Length—Series 99.)

Compression tests of 6 by 12-in. cylinders.
Hand-mixed concrete.
Mix by volume.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1¼ in.
Relative consistency, 1.00.
Specimens stored in damp sand; tested damp.
Age at test, 28 days.
Each value is the average of 20 tests made on different days

Extensometer Gage Length, in.	Water Ratio.	Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
					Initial Tangent.	For Different Percentages of Load.									
						Tangent Modulus.					Secant Modulus.				
						5	10	15	25	50	5	10	15	25	50
Mix 1:7.															
4	1.06	1740	419	0.756	3800	4900	3920	3400	2840	2290	6460	5250	4510	3760	2980
6		1810	475	0.773	3810	5070	3880	3540	2880	2280	7040	5350	4580	3810	2940
8		1830	500	0.784	3650	4640	3720	3280	2820	2360	6200	4960	4360	3700	3080
10		1750	594	0.804	3610	4430	3640	3290	2720	2290	5920	4640	4050	3450	2860
Average..........		1780	....	......	3720	4760	3790	3380	2820	2310	6400	5050	4380	3680	2970
Mix 1:5.															
4	0.86	2700	942	0.839	4240	4480	3910	3540	3210	2840	5520	4640	4270	3870	3410
6		2550	689	0.802	4280	4870	3720	3500	3140	2850	7390	5050	4500	3930	3340
8		2530	525	0.770	4080	5180	4050	3520	2990	2450	7310	5550	4740	3920	3140
10		2550	651	0.797	4120	4590	3780	3360	2920	2480	6030	4880	4310	3710	3100
Average..........		2580	....	......	4180	4780	3870	3480	3070	2660	6560	5030	4460	3860	3250
Mix 1:4.															
4	0.76	3100	1160	0.862	4490	4340	3780	3490	3280	2840	5150	4470	4130	3770	3350
6		3140	865	0.818	4510	5020	4140	3730	3310	2820	6460	5250	4690	4100	3450
8		3100	652	0.790	4090	5070	4090	3600	3070	2650	6900	5460	4680	3960	3280
10		3150	976	0.841	4300	4320	3710	3410	3090	2780	5320	4510	4120	3690	3220
Average..........		3120	....	......	4350	4690	3930	3560	3190	2770	5960	4920	4400	3880	3320
Mix 1:3.															
4	0.66	3520	905	0.821	4790	4830	4100	3720	3320	2850	6000	5040	4560	4050	3470
6		3370	965	0.830	4600	4630	3960	3540	3280	2840	5680	4830	4410	3950	3420
8		3480	1420	0.871	4490	4320	3790	3590	3260	2930	5390	4680	4340	3930	3480
10		3560	1370	0.873	4620	4560	3920	3640	3270	2900	5360	4590	4220	3790	3330
Average..........		3480	....	......	4620	4590	3940	3620	3280	2880	5610	4780	4380	3930	3420

TABLE XIII.—MODULUS OF ELASTICITY OF CONCRETE.

(Size and Grading of Aggregate, Mix and Consistency; Series 104.)

Compression tests of 6 by 12-in. concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.
Age at test 28 days.

Aggregate.		Water.		Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
							Initial Tangent.	For Different Percentages of Load.									
								Tangent Modulus.					Secant Modulus.				
Size.	F. M.	Relative Cons'y	Water Ratio.					5	10	15	25	50	5	10	15	25	50
							MIX 1:5.										
0–28	1.20	1.00	1.42	370	675	0.951	1130	1130	1070	1060	1030	1000	1190	1120	1120	1080	1050
0–14	2.25	1.00	1.29	550	464	0.884	1420	1350	1310	1250	1200	1120	1510	1460	1390	1320	1230
0–8	2.65	1.00	1.24	740	620	0.894	1820	1870	1660	1560	1460	1370	2160	1910	1790	1670	1560
0–4	3.00	1.00	1.20	960	585	0.857	2320	2500	2130	1980	1780	1620	3000	2540	2360	2090	1920
0–⅜	4.00	1.00	1.08	1370	843	0.874	2920	2990	2670	2490	2340	2110	3440	3070	2860	2680	2410
0–¾	5.00	1.00	0.96	2230	1230	0.875	4480	4140	3670	3420	3170	2940	4810	4250	3950	3650	3380
0–1½	5.75	1.00	0.88	2600	1590	0.897	4400	4230	3900	3750	3560	3320	4720	4310	4160	3940	3670
Average				1260	....	....	2640	2600	2340	2220	2080	1930	2980	2670	2520	2350	2170
							MIX 1:3.										
0–28	1.20	1.00	0.99	1020	810	0.889	2500	2510	2230	2170	1980	1810	2870	2540	2470	2260	2060
0–14	2.25	1.00	0.92	1620	1118	0.895	3080	3070	2870	2740	2590	2430	3400	3180	3030	2860	2690
0–8	2.65	1.00	0.89	1810	1058	0.887	3270	3060	2600	2610	2510	2250	3480	2950	2960	2840	2550
0–4	3.00	1.00	0.87	2330	941	0.857	4000	3650	3220	3040	2810	2480	4280	3760	3550	3270	2880
0–⅜	4.00	1.00	0.80	3460	1608	0.902	4680	3930	3640	3520	3310	3120	4350	4030	3890	3660	3460
0–¾	5.00	1.00	0.72	4020	1557	0.901	4440	3780	3510	3410	3230	2930	4200	3900	3790	3590	3250
0–1½	5.75	1.00	0.67	4140	1502	0.893	4480	3900	3560	3440	3210	2900	4390	4000	3860	3590	3240
Average				2630	....	....	3780	3410	3090	2990	2810	2560	3850	3480	3360	3150	2880
							MIX 1:5.										
0–1½	4.00	1.00	1.08	1510	1143	0.890	3480	3380	3150	2960	2770	2570	3860	3580	3360	3130	2890
0–1½	5.00	1.00	0.96	2250	1242	0.867	4580	4610	4070	3890	3550	3240	5340	4720	4500	4110	3750
0–1½	5.50	1.00	0.90	2650	1742	0.921	3900	3710	3460	3320	3230	3040	4050	3770	3610	3510	3290
0–1½	5.75	1.00	0.88	2830	1428	0.882	4580	4550	4000	3810	3460	3160	5200	4570	4350	3920	3600
0–1½	6.00	1.00	0.84	2730	1390	0.875	5080	4690	4140	3940	3640	3290	5420	4760	4520	4160	3750
0–1½	6.25	1.00	0.82	2300	1200	0.879	3940	3890	3480	3240	3090	2820	4520	3990	3700	3510	3180
0–1½	6.50	1.00	0.78	1680	1445	0.901	3300	3720	3550	3400	3220	2930	4140	3950	3780	3580	3250
Average				2280	....	....	4120	4080	3690	3510	3280	3010	4650	4190	3970	3700	3390
							MIX 1:7.										
0–1½	5.75	0.90	0.97	2070	1153	0.862	4800	4790	4070	3720	3420	3040	5650	4790	4370	4000	3530
		1.00	1.08	1690	674	0.802	5180	5220	4420	3810	3360	2860	6850	5720	4870	4250	3580
		1.10	1.19	1400	902	0.846	4180	4830	4100	3660	3260	2840	6120	5160	4570	4030	3480
		1.25	1.35	940	603	0.831	3460	3840	3300	2990	2610	2210	4930	4210	3780	3270	2730
		1.50	1.62	770	453	0.814	3130	3820	2860	2550	2240	1910	5370	3790	3290	2810	2320
Average				1370	....	....	4150	4500	3750	3350	2980	2570	5780	4730	4180	3670	3130

TABLE XIII.—*Continued.*

Aggregate.		Water.		Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
							Initial Tangent.	For Different Percentages of Load.									
								Tangent Modulus.					Secant Modulus.				
Size.	F. M.	Relative Cons'y	Water Ratio.					5	10	15	25	50	5	10	15	25	50
Mix 1:5.																	
0–1½	5.75	0.90	0.79	3260	1089	0.853	5060	4370	3660	3550	3280	2960	5220	4330	4170	3820	3430
		1.00	0.88	2770	1442	0.888	4440	4270	3900	3670	3490	3160	4820	4390	4130	3930	3560
		1.10	0.96	2090	1104	0.849	4820	4830	4460	4020	3640	3230	5820	5350	4820	4310	3830
		1.25	1.09	1450	578	0.794	4520	4780	4050	3610	3170	2630	6100	5150	4570	4000	3300
		1.50	1.31	990	731	0.870	3450	2980	2560	2350	2150	1910	3650	3080	2820	2550	2230
Average				2110	....	....	4460	4250	3730	3440	3150	2780	5120	4460	4100	3720	3270
Mix 1:4.																	
0–1½	5.75	0.90	0.70	4180	1652	0.922	3360	3240	3060	3000	2860	2780	3510	3310	3240	3090	3000
		1.00	0.77	3340	1396	0.866	5360	4960	4470	4200	3810	3460	5750	5170	4860	4410	4000
		1.10	0.85	2760	1932	0.912	4600	4430	4100	4000	3770	3530	4870	4490	4380	4120	3850
		1.25	0.96	1640	984	0.852	4280	4270	3860	3520	3260	2930	5050	4550	4150	3840	3450
		1.50	1.16	1130	1072	0.894	3700	3180	2890	2750	2570	2350	3630	3270	3090	2870	2610
Average				2610	....	....	4260	4020	3680	3490	3250	3010	4560	4160	3940	3670	3380
Mix 1:3.																	
0–1½	5.75	0.90	0.60	4690	2820	0.924	5220	4600	4340	4130	3930	3660	5030	4740	4510	4280	3980
		1.00	0.67	3950	1976	0.907	5320	4400	4250	4110	3910	3580	4860	4690	4530	4300	3920
		1.10	0.74	3570	2104	0.926	5060	4730	4430	4370	4190	3900	5090	4750	4680	4510	4200
		1.25	0.84	2520	1652	0.898	4600	4400	4040	3850	3690	3460	4910	4490	4280	4090	3840
		1.50	1.00	1570	800	0.847	4050	3600	3200	3000	2720	2320	4320	3810	3560	3200	2720
Average				3260	....	....	4850	4350	4050	3890	3690	3380	4840	4500	4310	4080	3730
Mix 1:2.																	
0–1½	5.75	0.90	0.51	4780	1355	0.869	4800	4360	3900	3600	3380	3000	5130	4560	4210	3950	3480
		1.00	0.57	4500	1887	0.907	4780	4400	4060	3840	3720	3380	4920	4520	4270	4120	3740
		1.10	0.62	4070	1718	0.884	5320	4960	4440	4070	3940	3520	5730	5110	4660	4500	4010
		1.25	0.71	2790	1112	0.851	4760	4860	4210	3890	3600	3170	5780	4980	4590	4240	3720
		1.50	0.85	1840	1690	0.919	4020	3860	3610	3460	3280	3100	4320	4000	3810	3580	3370
Average				3600	....	....	4740	4490	4040	3770	3580	3230	5180	4630	4310	4080	3660
Mix 1:1.																	
0–1½	5.75	0.90	0.42	5850	1342	0.888	4940	4220	3860	3670	3460	3050	4760	4350	4110	3890	3430
		1.00	0.46	5150	1725	0.903	4680	4110	3840	3660	3470	3250	4570	4270	4080	3860	3620
		1.10	0.51	5070	1164	0.876	3960	3420	3110	2990	2760	2360	3910	3560	3420	3150	2700
		1.25	0.58	3830	1982	0.916	4660	4290	4080	3950	3800	3600	4660	4430	4280	4120	3890
		1.50	0.70	3440	1990	0.934	3930	3630	3460	3440	3330	3180	3890	3700	3670	3550	3370
Average				4670	....	....	4430	3930	3670	3540	3360	3090	4360	4060	3910	3710	3400

TABLE XIII.—*Continued.*

Aggregate.		Water.		Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
							Initial Tangent.	For Different Percentages of Load.									
								Tangent Modulus.					Secant Modulus.				
Size.	F. M.	Relative Cons'y	Water Ratio.					5	10	15	25	50	5	10	15	25	50
							MIX 1:½.										
0-1½	5.75	0.90	0.35	6380	1267	0.873	4620	3770	3420	3230	2990	2680	4340	3940	3710	3420	3060
		1.00	0.39	6680	1274	0.876	4580	3560	3260	3100	2810	2520	4110	3740	3540	3210	2860
		1.10	0.43	5720	1726	0.905	4500	3870	3680	3630	3330	3100	4290	4080	3910	3670	3420
		1.25	0.49	5380	1377	0.908	3300	2960	2780	2660	2550	2350	3280	3070	2940	2810	2580
		1.50	0.59	4120	1094	0.859	4380	3830	3380	3170	2980	2620	4620	4040	3760	3510	3060
Average.				5660	....	....	4280	3600	3300	3160	2930	2650	4130	3770	3570	3320	3000
							NEAT.										
		0.90	0.32	4140	1222	0.905	3400	2800	2640	2620	2510	2370	3070	2890	2870	2740	2580
		1.00	0.36	7600	1371	0.898	4200	3110	2820	2700	2500	2270	3470	3140	3000	2790	2530
		1.10	0.40	6630	867	0.854	3660	2860	2550	2350	2150	1900	3360	2990	2750	2510	2210
		1.25	0.45	6360	1106	0.876	4340	3020	2740	2600	2390	2180	3510	3140	2960	2700	2440
		1.50	0.54	4930	832	0.873	3120	2420	2220	2100	1950	1780	2760	2510	2360	2170	1960
Average.				5930	....	....	3740	2840	2590	2470	2300	2100	3230	2930	2790	2580	2340

Relation between Modulus of Elasticity and Compressive Strength.—The Joint Committee on Concrete[1] recommends "that in computations for the position of the neutral axis, and for the resisting moment of beams and for compression of concrete in columns, the modulus of elasticity be assumed as:

"(*a*) One-fortieth that of steel, when the strength of the concrete is taken as not more than 800 lb. per sq. in.

"(*b*) One-fifteenth that of steel, when the strength of the concrete is taken as greater than 800 lb. per sq. in. and less than 2200 lb. per sq. in.

"(*c*) One-twelfth that of steel, when the strength of the concrete is taken as greater than 2200 lb. per sq. in. and less than 2900 lb. per sq. in. and

"(*d*) One-tenth that of steel, when the strength of the concrete is taken as greater than 2900 lb. per sq. in.

"Although not rigorously accurate, these assumptions will give safe results. For the deflection of beams which are free to move longitudinally at the supports, in using

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part I, p. 202 (1917).

TABLE XIV.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Amount of Cement, Size of Aggregate; Series 114.)

Compression tests of 6 by 12-in. concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Aggregate.		Water.		Compressive Strength, lb. per sq. in.			Initial Tangent Modulus, 1000 lb. per sq. in.			Tangent Modulus, 1000 lb. per sq. in. at 25 per cent Load,		
	Size.	F.M.	Relative Consistency.	Water Ratio.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.
1:4	0–1½	5.80	0.90	0.66	2440	3920	4400	4100	5400	6460	3520	3950	4740
	....	....	0.95	0.69	2150	3470	4410	3500	4800	5700	3190	3700	4710
	....	....	1.00	0.73	2090	3310	4580	4000	5400	5960	3310	4310	4690
	....	....	1.05	0.76	1850	3140	4430	3500	4400	6700	3090	3330	4590
	....	....	1.10	0.80	1570	3120	4130	3000	5300	5720	2590	4040	5470
	....	....	1.25	0.91	1080	2260	2950	2800	4080	5160	2490	3300	4280
	....	....	1.50	1.01	670	1320	2150	2300	2900	4600	2050	2620	3570
	....	....	2.00	1.46	400	860	1240	1100	2600	4060	....	2650	3480
1:9	0–1½	5.80	1.00	1.23	570	1070	1480	1600	2700	3920	2820	3270	3290
1:6	....	....	....	0.93	....	2060	2060	....	4500	....	....	3480	....
1:5	....	....	....	0.83	1470	2680	3460	3300	4900	5120	2830	3790	4230
1:4	....	....	....	0.73	2090	3310	4580	4000	5400	5960	3310	4310	4690
1:3	....	....	....	0.63	2620	4030	4690	4500	5600	6900	3390	4190	5160
1:2	....	....	....	0.53	....	4870	....	....	5500	....	....	4330	....
1:4	0–14	2.20	1.00	1.13	....	970	....	....	1800	....	....	1580	....
	0–8	2.60	....	1.07	....	1170	....	....	1900	....	....	1880	....
	0–4	3.10	....	1.00	....	1360	....	....	2700	....	....	2400	....
	0–⅜	4.50	....	0.83	....	2490	....	....	4200	....	....	3440	....
	0–¾	5.40	....	0.77	....	3530	....	....	4900	....	....	3760	....
	0–1½	5.80	....	0.73	2090	3310	4580	4000	5400	5960	3310	4310	4690

Mix by Vol.	Aggregate.		Water.		Compressive Strength, lb. per sq. in.			Secant Modulus at 25 per cent Load, 1000 lb. per sq. in.			Value of *K* in 1000 lb. per sq. in.			Value of *n*.		
	Size.	F. M.	Relative Consistency.	Water Ratio.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.
1:4	0–1½	5.80	0.90	0.66	2440	3920	4400	3720	4370	5100	2345	2000	2870	.947	.904	.930
			0.95	0.69	2150	3470	4410	3300	4120	5210	2322	1738	2318	.966	.898	.905
			1.00	0.73	2090	3310	4580	3550	4660	5180	1914	2415	2328	.932	.924	.906
			1.05	0.76	1850	3140	4430	3300	3800	5230	1850	1227	1782	.937	.875	.877
			1.10	0.80	1570	3120	4130	2660	4420	5960	2110	2080	2970	.971	.914	.918
			1.25	0.91	1080	2260	2950	2650	3540	4700	1556	1910	2162	.940	.931	.910
			1.50	1.01	670	1320	2150	2300	2780	3920	830	1698	1762	.892	.944	.911
			2.00	1.46	400	860	1240	....	3160	3760	596	668	1928	.956	.837	.926
1:9	0–1½	5.80	1.00	1.23	570	1070	1480	3000	3710	3500	713	1038	2028	.921	.882	.940
1:6	..	....	....	0.93	....	2060	2060	....	3820	....	....	1734	....	....	.912	....
1:5	..	....	....	0.83	1470	2680	3460	2960	4220	4610	2042	1730	2223	.955	.899	.918
1:4	..	....	....	0.73	2090	3310	4580	3550	4660	5180	1914	2415	2328	.932	.924	.906
1:3	..	....	....	0.63	2620	4030	4690	3640	4650	5700	1995	2046	2518	.931	.904	.905
1:2	..	....	....	0.53	....	4870	....	....	4660	....	....	2558	....	....	.928	....
1:4	0–14	2.20	1.00	1.13	....	970	....	....	1640	....	..	1462	....	....	.965	....
	0–8	2.60	....	1.07	....	1170	....	....	1960	....	....	1397	....	....	.960	....
	0–4	3.10	....	1.00	....	1360	....	....	2640	....	....	1186	....	....	.910	....
	0–⅜	4.50	....	0.83	....	2490	....	....	3710	....	....	1950	....	....	.928	....
	0–¾	5.40	....	0.77	....	3530	....	....	4150	....	....	1875	....	....	.908	....
	0–1½	5.80	....	0.73	2090	3310	4580	3550	4660	5180	1914	2415	2328	.932	.924	.906

formulas for deflection which do not take into account the tensile strength developed in the concrete, a modulus of one-eighth of that of steel is recommended."

A study of this recommendation leads one to the conclusion that it is probably based on the assumption that the ratio of modulus of elasticity to the compressive strength of concrete is about 1000.

TABLE XV.—RATIO OF MODULUS OF ELASTICITY OF CONCRETE TO COMPRESSIVE STRENGTH.

(Data from Table XIV.)

Compression tests of 6 by 12-in. concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Aggregate.		Water.		Ratio of Modulus of Elasticity to Ultimate Compressive Strength								
	Size.	F. M.	Relative Consistency.	Water Ratio.	Initial Tangent.			Tangent at 25 per cent Load.			Secant at 25 per cent Load.		
					7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.	7 d.	28 d.	3 mo.
1:4	0–1½	5.80	0.90	0.66	1680	1380	1470	1440	1010	1080	1520	1110	1160
			0.95	0.69	1630	1380	1290	1480	1070	1070	1530	1190	1180
			1.00	0.73	1910	1630	1300	1580	1300	1020	1700	1410	1130
			1.05	0.76	1890	1400	1510	1670	1060	1030	1780	1210	1180
			1.10	0.80	1910	1690	1390	1650	1280	1330	1700	1410	1450
			1.25	0.91	2590	1810	1750	2300	1460	1450	2450	1570	1590
			1.50	1.01	3440	2200	2140	3060	1980	1660	3440	2100	1820
			2.00	1.46	2750	3020	3280	....	3080	2800	....	3680	3040
1:9	0–1½	5.80	1.00	1.23	2810	2520	2650	4950	3060	2220	5260	3470	2360
1:6	....	....	....	0.93	....	2190	....	....	1690	....	....	1850	....
1:5	....	....	....	0.83	2240	1830	1480	1920	1420	1220	2010	1580	1330
1:4	....	....	....	0.73	1910	1630	1300	1580	1300	1020	1700	1410	1130
1:3	....	....	....	0.63	1720	1390	1470	1290	1040	1100	1380	1150	1220
1:2	....	....	....	0.53	....	1130	....	....	890	....	....	960	....
1:4	0–14	2.20	1.00	1.13	....	1860	....	....	1630	....	....	1690	....
	0–8	2.60	....	1.07	....	1620	....	....	1610	....	....	1680	....
	0–4	3.10	....	1.00	....	1990	....	....	1770	....	....	1940	....
	0–⅜	4.50	....	0.83	....	1690	....	....	1380	....	....	1490	....
	0–¾	5.40	....	0.77	....	1390	....	....	1060	....	....	1170	....
	0–1½	5.80	....	0.73	1920	1630	1300	1580	1300	1020	1700	1410	1130

Taylor and Thompson[1] state that while there is probably some relation between strength and modulus of elasticity, it is so complex that it will probably never be discovered. They give 1300 as the approximate ratio of modulus of elasticity to strength.

Falk[2] concludes that the modulus of elasticity as determined by compression tests is 1325 times the ultimate strength of the concrete.

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[1] Taylor and Thompson, "Concrete, Plain and Reinforced."

[2] Falk, "Cements, Mortars and Concretes."

Thacher gives the following formulas derived from Kimball's tests for concrete of different ages, which do not take into account directly the compressive strength:

THACHER'S FORMULAS FOR MODULUS OF ELASTICITY.

7 days old.......... $E=2{,}600{,}000 - 700{,}000\left(\frac{\text{volume of sand}}{\text{volume of cement}}-2\right)$.
1 month old.......... $E=2{,}900{,}000 - 300{,}000\,($ " $-1)$.
3 months old.......... $E=3{,}600{,}000 - 500{,}000\,($ " $-2)$.
6 months old.......... $E=3{,}600{,}000 - 600{,}000\,($ " $-3)$.

If the term $\left(\frac{\text{volume of sand}}{\text{volume of cement}}-c\right)$ is zero or becomes a negative quality, the entire term is to be considered zero.

All of the above relations with the exception of Thacher's assume a constant ratio between the modulus of elasticity and strength. Thacher's formulas are of limited application since they do not take into account such important variables as the grading of the aggregate and the consistency of concrete.

Schüle[1] evolves an equation for the "relation between coefficient of elasticity of concrete (in tons per sq. cm.) and its crushing strength (kilos. per sq. cm.)" as follows:

$$E_b=\frac{B^2-25.16B+50.38}{0.001646B^2+0.224B+7.65}$$

in which E_b = modulus of elasticity of concrete, tons per sq. cm. and B = ultimate compressive strength, kg. per sq. cm.

In units of pounds per square inch this equation may be written,

$$E_b=\frac{70B^2-25\,100B+717\,000}{0.000008B^2+0.0157B+7.65}$$

While this equation, in our opinion, more nearly represents the true form of the relation than any of those quoted from other writers, it is open to the objection that negative values for E_b are obtained for values of B less than 22.96 kg. per sq. cm. (330 lb. per sq. in.)

Our tests show that the relation between modulus of elasticity and strength for mixes ranging from 1:15 to about 1:3

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[1] *Proceedings*, Sixth Congress, Inter. Assoc. Test. Mats., New York, 1912, Second Section.

may be represented by a single curve, but the relation is not linear. Ratios ranging from about 4000 for the low strengths to 1000 for the high strengths are found.

The relation between modulus of elasticity and strength of concrete from tests covered in this report may be represented by the equation,

$$E = CS^m \quad \text{.....................} \quad (8)$$

where E = modulus of elasticity of concrete, C = a constant depending on the conditions of the test, S = ultimate strength of concrete, and m = an exponent (less than 1).

For the different series of tests, the constants vary over a considerable range. However, in cases where C is larger than the average, m is smaller, and therefore for ordinary ranges in strength the values of modulus of elasticity given by the equations from the different series of tests show a good agreement.

Fig. 23 shows the relation for initial tangent modulus to compressive strength for concrete made from four different sizes of pebble aggregate and one size of limestone aggregate, for consistencies ranging from very dry to sloppy mixes, and for ages ranging from 7 days to 1 year. The curve in this figure may be represented by the equation,

$$E_i = 45{,}500\, S^{0.58} \quad \text{..................} \quad (9)$$

The points on this diagram are more scattered than for others, due to three causes:

1. Each value is the average of 5 or less tests. Our experience has shown that moduli of elasticity should be the average of 10 or more tests to give concordant results.
2. All readings except those for the 1-year tests were taken with the Johnson wire-wound dial, which does not give as uniform results as the Ames instrument.
3. Some of the mixtures (those represented by relative consistencies less than 0.90) were too dry to make a plastic concrete and hence gave erratic results.

The data from Fig. 23 are shown in Fig. 24 except that the average of all the consistencies in each group is platted instead of individual values. An equation having the same constants is found. The curve is more uniform because each value is the average of about 30 tests instead of 5. This diagram brings out pointedly the fact that the relation between strength and modulus

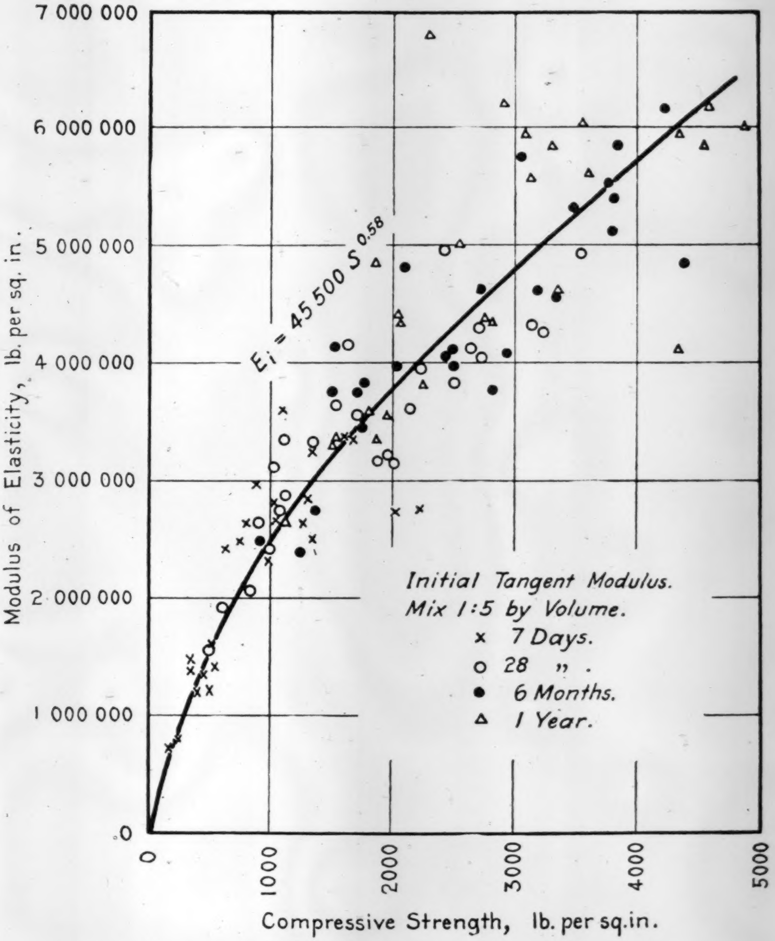

FIG. 23.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table IV.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
Compare Figs. 24 to 33 inclusive.

of elasticity for ages varying from 7 days to 1 year can be represented by the same curve.

Fig. 25 gives a similar relation for another series of tests. The concrete represented by this figure was machine mixed. The mix was 1:4, using 0–1½-in. pebble aggregate and consistencies ranging from very dry to sloppy. Tests were made at ages of 7 and 28 days and 2 months. For these data the relation between strength and modulus of elasticity is expressed by the equation,

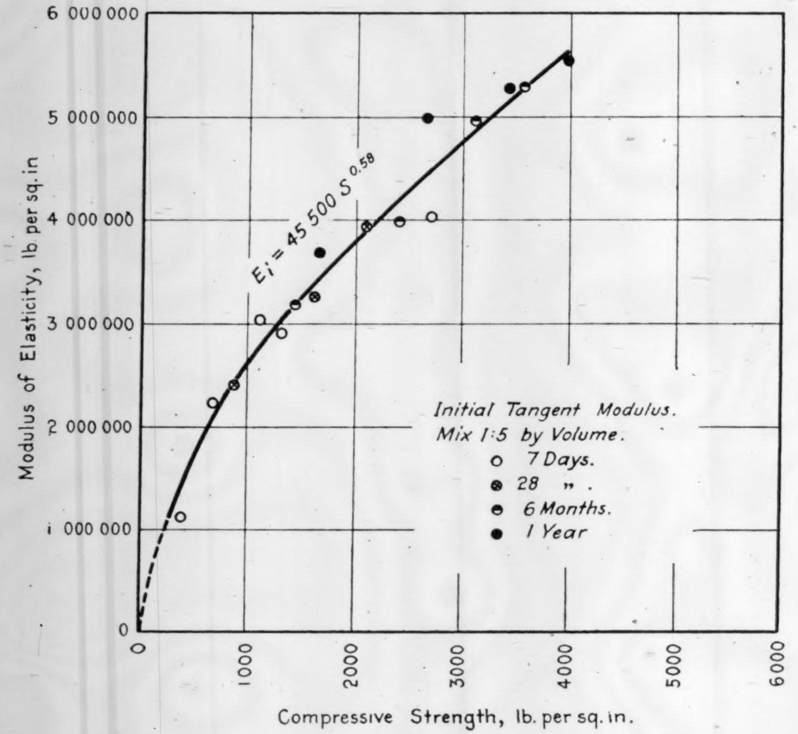

FIG. 24.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table IV.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
Each value is the average of 30 to 35 tests from 6 or 7 consistencies.
Compare Figs. 23 and 25 to 33 inclusive.

$$E_i = 90{,}000\, S^{0.50} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

These constants are considerably different from those in the two preceding figures, but a comparison of the curves over the ordinary range will show that there is no great difference in the modulus of elasticity for a given strength. For example, in Fig. 25 for a concrete having an ultimate strength of 1000

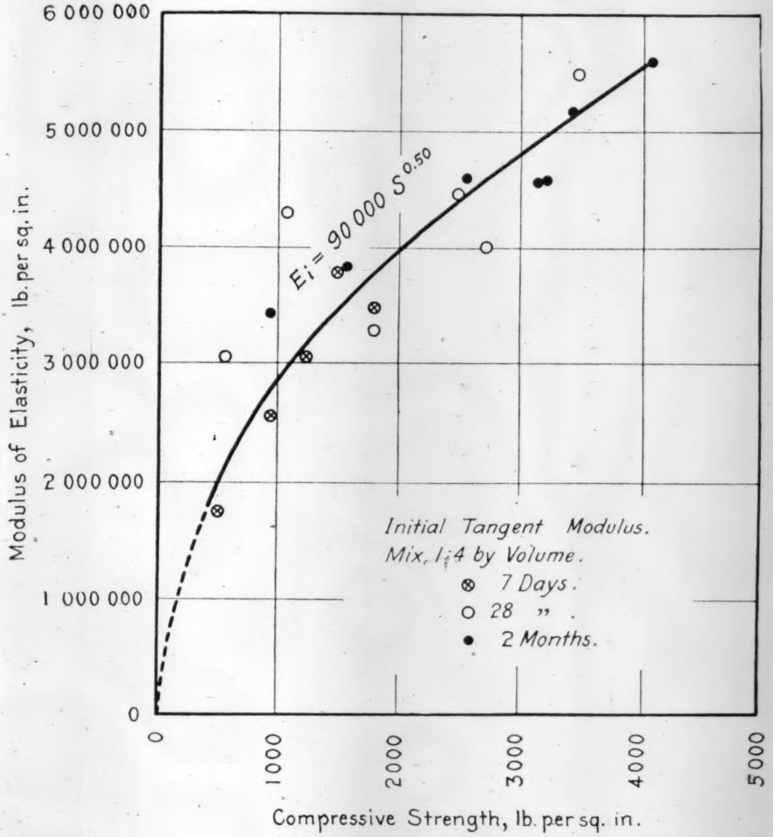

FIG. 25.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table V.
Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Each value is the average of 24 tests from 6 times of mixing.
Compare Figs. 23, 24, and 26 to 33 inclusive.

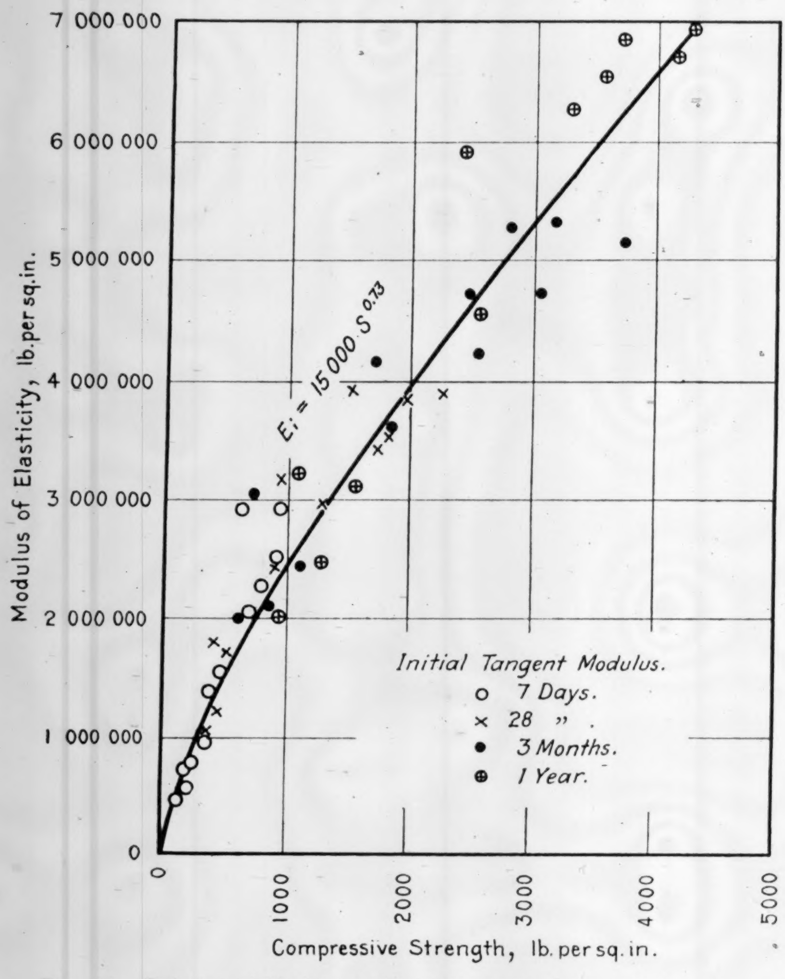

FIG. 26.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table VII.
Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Figs. 23 to 25 and 27 to 33 inclusive.

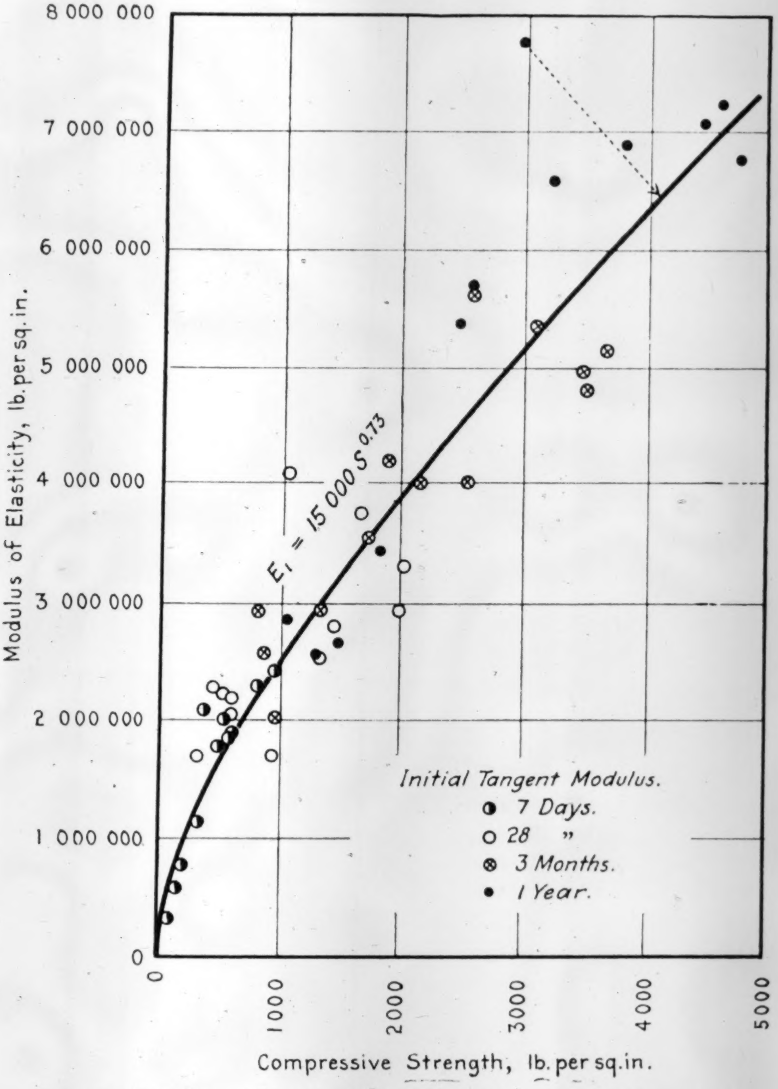

FIG. 27.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table VIII.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Compare Figs. 23 to 26 and 28 to 33 inclusive.

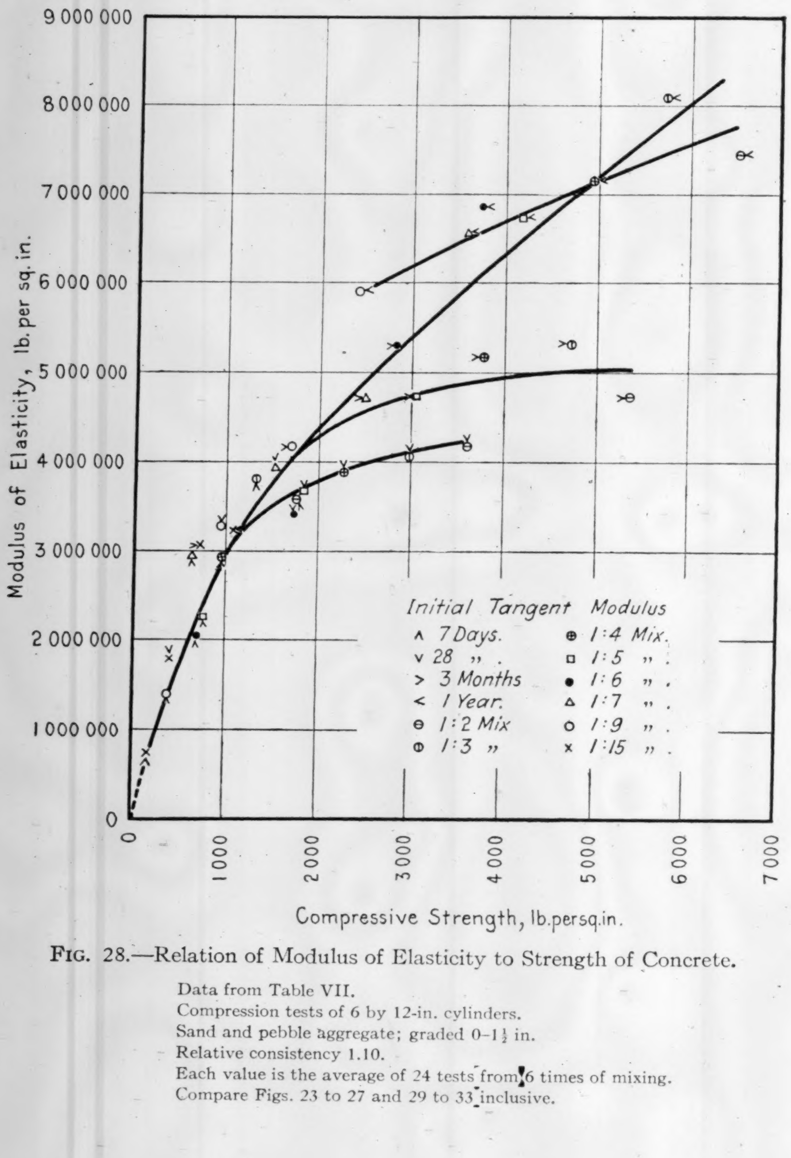

FIG. 28.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table VII.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Figs. 23 to 27 and 29 to 33 inclusive.

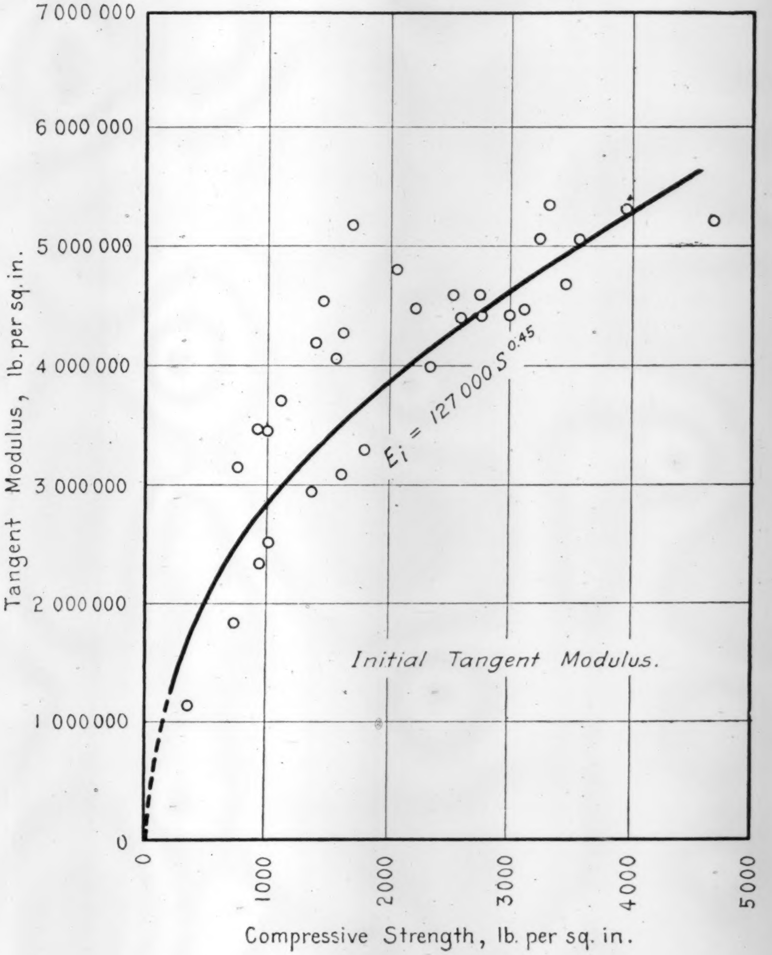

FIG. 29.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 23 to 28 and 30 to 33 inclusive.

lb. per sq. in. the average curve gives a modulus of elasticity of 2,800,000 lb. per sq. in., while for the two preceding curves the average is 2,500,000 lb. per sq. in. For 2000-lb. concrete the discrepancy is still less, the values obtained being 4,000,000 and 3,800,000 lb. per sq. in. respectively.

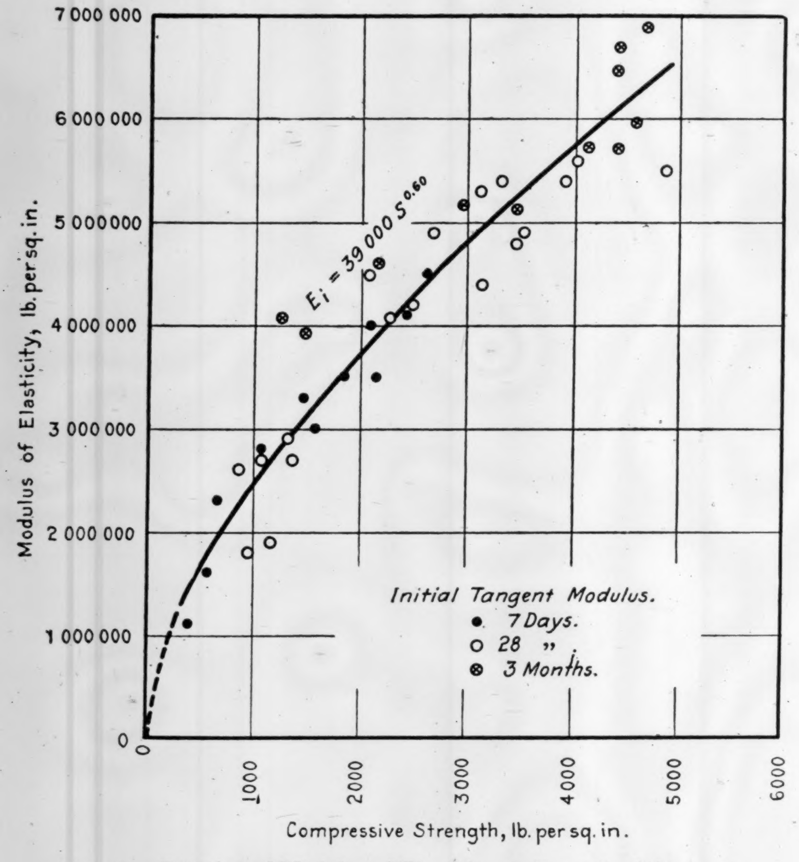

FIG. 30.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table XIV.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 23 to 29 and 31 to 33 inclusive.

Figs. 26 and 27 give the data from Tables VII and VIII. The mixtures ranged from 1:15 to 1:3, the consistency was 1.10, and the aggregate ranged in size from 0–28 sand to 0–2-in. gravel. Data in Table VII are for machine-mixed concrete from 6 times of mixing, ranging from $\frac{1}{4}$ to 10 minutes. Values are given in Table VIII for hand-mixed concrete of the same composition. The constants for these equations are the same; in other words, there is no difference between machine-mixed and hand-mixed concrete so far as the relation of modulus of elasticity to strength is concerned. It will be noted that there

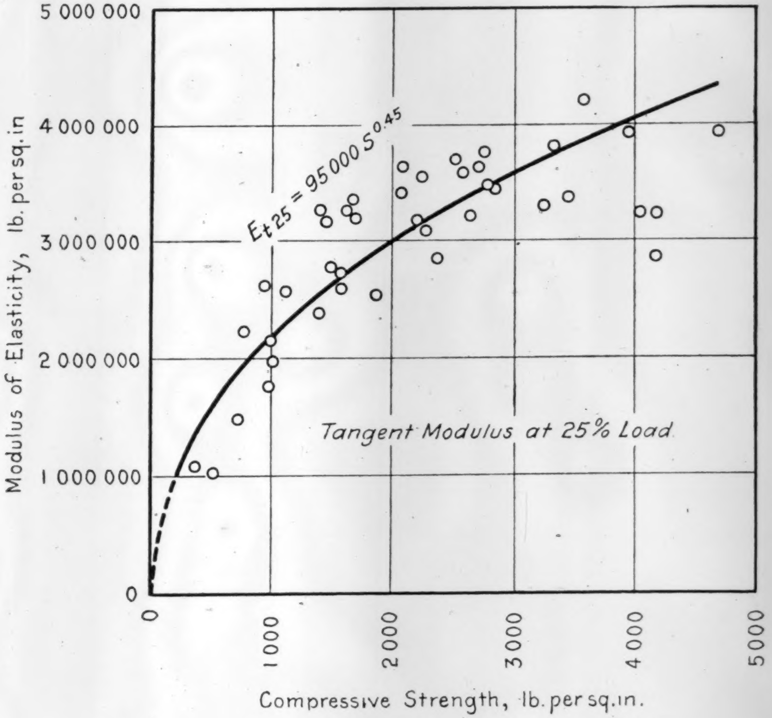

FIG. 31.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 23 to 30 inclusive, 32 and 33.

is considerable difference between the constants for these curves and those given in Figs. 23 to 25. However, a direct comparison will show that the differences in moduli of elasticity for concrete of given strengths are not as great as the difference in constants might at first seem to indicate. In Figs. 26 and 23 the moduli of elasticity for 1000 and 2000-lb. concrete are almost the same. It is for the higher strengths that the difference is more pronounced. In Fig. 26, 4000-lb. concrete gives a modulus of elasticity of 6,600,000 lb. per sq. in., while Fig. 23 gives 5,700,000 lb. per sq. in.

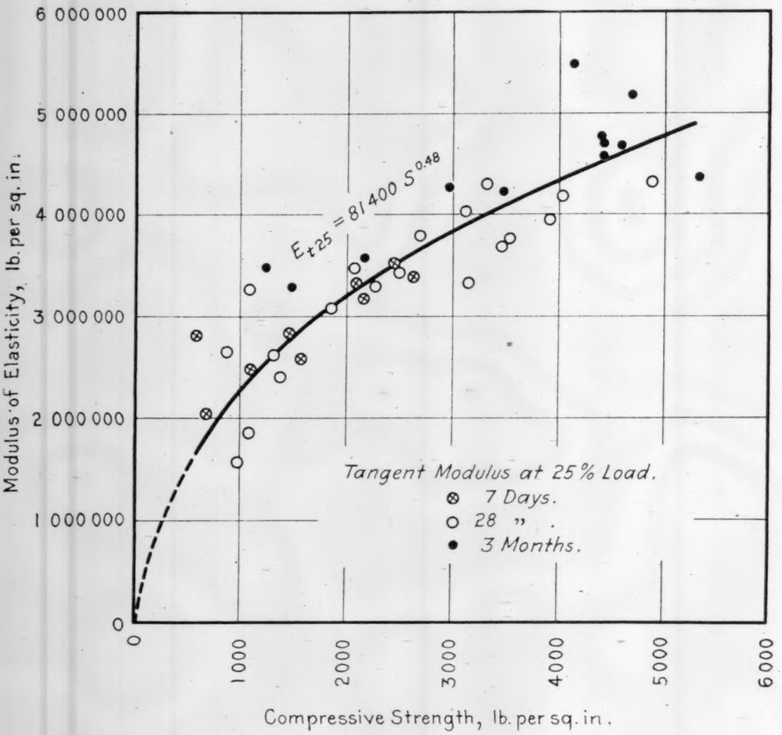

FIG. 32.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table XIV.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Figs. 23 to 31 inclusive and 33.

TABLE XVI.—MODULUS OF ELASTICITY OF CONCRETE.

Values taken from the curves in Figs. 23 to 32, inclusive.

The average values for "Initial Tangent" Modulus are represented by the equation:

$$E_i = 40{,}000\, S^{0.60}$$

For Tangent Modulus at 25 per cent Load:

$$E_{t25} = 84{,}300\, S^{0.475}$$

In the above equation S is the Compressive Strength.

Data from Series.	For Details of Tests see Table.	Modulus of Elasticity, 1000 lb. per sq. in. for Ultimate Strength (lb. per sq. in.).						
		500	1000	1500	2000	3000	4000	5000
		INITIAL TANGENT MODULUS (E_i).						
83	III	1600	2450	3150	3750	4800	5700	6600
89	IV	2000	2800	3450	3950	4800	5550	....
93*a*	VI	1400	2300	3000	3800	5200	6500	....
93	VII	1400	2300	3100	3800	5100	6300	7400
104	XII	2060	2840	3420	3890	4640	5300	6600
114	XIII	1700	2500	3150	3700	4800	5800	6870
Average		1690	2530	3210	3820	4890	5860	7000
		TANGENT MODULUS AT 25 PER CENT LOAD (E_t).						
99	XI	....	....	2500	2750	3200	3500	....
104	XII	1550	2130	2560	2920	3480	3970	....
114	XIII	1500	2280	2800	3200	3830	4330	4770
Average		1520	2200	2620	2920	3630	4350	4770

[a] Machine mixed.

TABLE XVII.—AVERAGE VALUES OF MODULUS OF ELASTICITY From Nomographic Chart Fig. 37.

Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
			Initial Tangent.	For Different Percentages of Load.									
				Tangent Modulus.					Secant Modulus.				
				5	10	15	25	50	5	10	15	25	50
500	665	0.90	2100	1950	1720	1640	1550	1450	2170	1910	1820	1720	1610
1000	955	0.90	2900	2700	2380	2260	2140	2000	3000	2650	2510	2380	2220
1500	1200	0.90	3400	3160	2790	2650	2510	2350	3510	3160	2940	2790	2610
2000	1335	0.90	3900	3630	3200	3040	2890	2690	4040	3560	3380	3210	2990
3000	1674	0.90	4700	4370	3850	3670	3480	3240	4860	4280	4080	3870	3600
4000	1910	0.90	5300	4920	4350	4130	3920	3660	5470	4840	4600	4360	4070
5000	2186	0.90	5900	5500	4840	4600	4370	4070	6110	5380	5110	4860	4520

Fig. 28 gives data from Group 1 of Table VII, for mixtures ranging from 1:15 to 1:2 and ages ranging from 7 days to 1 year. All of the aggregates were of one size, being graded up to 1½ in. The consistency was such as might be used in ordinary concrete road mixtures. The richer mixes show a falling-off from the average curve. Reference to Fig. 17 emphasizes this point. This would indicate that the general relation given in Eq. 8 does not hold for mixes richer than about 1:3.

Figs. 29 and 30 show the relation between modulus of elasticity and strength for data from Tables XIII and XIV. In Fig. 29 mixes richer than 1:3 were omitted. For these tests values of modulus of elasticity were calculated at various percentages of load. Figs. 31 and 32 show this relation for the tangent modulus at 25 per cent of the compressive strength. These curves follow the same general law as those for initial tangent modulus, but give results about 15 to 25 per cent lower.

In Table XVI the average values for initial tangent modulus and tangent modulus at 25 per cent of the compressive strength taken from Figs. 23 to 32 inclusive are tabulated. As pointed out above, while the constants of these equations vary over a considerable range the values of modulus of elasticity obtained are not greatly different.

The grand average of all tests may be represented by the following equations:

$$E_i = 40{,}000\ S^{0.60} \tag{11}$$

$$E_{t25} = 84{,}300\ S^{0.47} \tag{12}$$

Without appreciable error they may be written:

$$E_i = 33{,}000\ S_{\frac{5}{8}} \tag{13}$$

$$E_{t25} = 66{,}000\ S_{\frac{1}{2}} \tag{14}$$

It may be of interest to note that Eq. 11 is based on about 2500 tests of 6 by 12-in. cylinders and Eq. 12 on about 800 tests.

The following table shows a comparison of moduli of elasticity obtained from Eq. 11 and equations given by other writers:

Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in., from				
	Eq. 11.	Schüle's Equation.	Taylor and Thompson's Ratio.	Falk's Ratio.	Joint Committee's Ratio.
1000	2 520 000	1 430 000	1 300 000	1 325 000	1 000 000
1500	3 170 000	2 430 000	1 950 000	1 990 000	1 500 000
2000	3 820 000	3 360 000	2 600 000	2 650 000	2 000 000
2500	4 440 000	3 850 000	3 250 000	3 320 000	2 500 000
3000	4 800 000	4 400 000	3 900 000	3 980 000	3 000 000
4000	5 900 000	5 110 000	5 200 000	5 300 000	4 000 000
5000	6 660 000	5 640 000	6 500 000	6 630 000	5 000 000

Fig. 33 shows data from Table IV with the modulus of elasticity expressed as a ratio to the compressive strength of the concrete. This ratio varies from about 4100 for 200-lb. concrete to about 1200 for 5000-lb. concrete.

MODULUS OF ELASTICITY OF CONCRETE AT DIFFERENT PERCENTAGES OF THE COMPRESSIVE STRENGTH.

The strength - modulus-of-elasticity relation has been shown only for the initial tangent and tangent modulus at 25 per cent of the compressive strength. Obviously tangent and secant moduli for all percentages of the load could not be presented. The values for initial tangent modulus were given prominence because of their general use. The tangent modulus at 25 per cent of the compressive strength was selected as being representative. In order that complete information may be had for all measures of modulus of elasticity their inter-relation will be shown.

In Fig. 34 the tangent moduli at the different percentages of the compressive strength are platted against the initial tangent moduli for the data given in Table XIII. The average of all the consistencies are platted for each mix. A straight line is obtained showing this relation to be of the form,

$$E_t = b_1 E_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

where b_1 is a constant, depending on the percentage of the compressive strength at which E_t is measured.

For the same data the ratio of tangent modulus to secant modulus is 0.90 (average value of n). Therefore the following equation may be written:

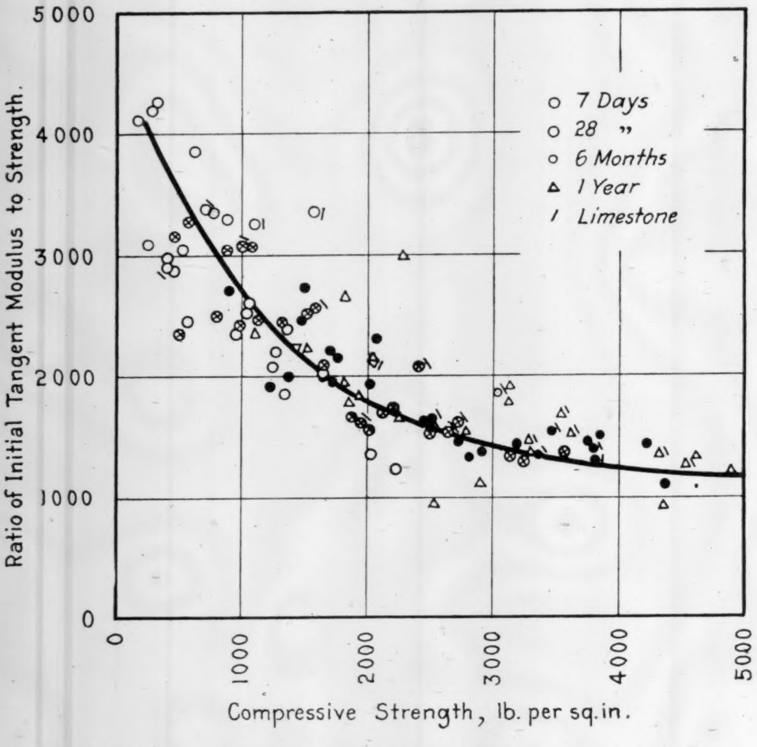

FIG. 33.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table IV.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
Compare Figs. 23 to 32 inclusive.

$$E_s = b_2 E_i \qquad (16)$$

where $b_2 = \dfrac{b_1}{0.9}$.

Fig. 35 shows the tangent and secant moduli at different percentages of the compressive strength expressed as a ratio to the initial tangent modulus (values of b_1 and b_2).

It was stated above that the initial tangent modulus is equal to the secant modulus at about 5 to 15 per cent of the compressive strength. Reference to Fig. 35 will show that the line marked Secant crosses the 100-per-cent line at about 5 per cent of the compressive strength. In other words the initial tangent modulus is equal to the secant modulus at this point.

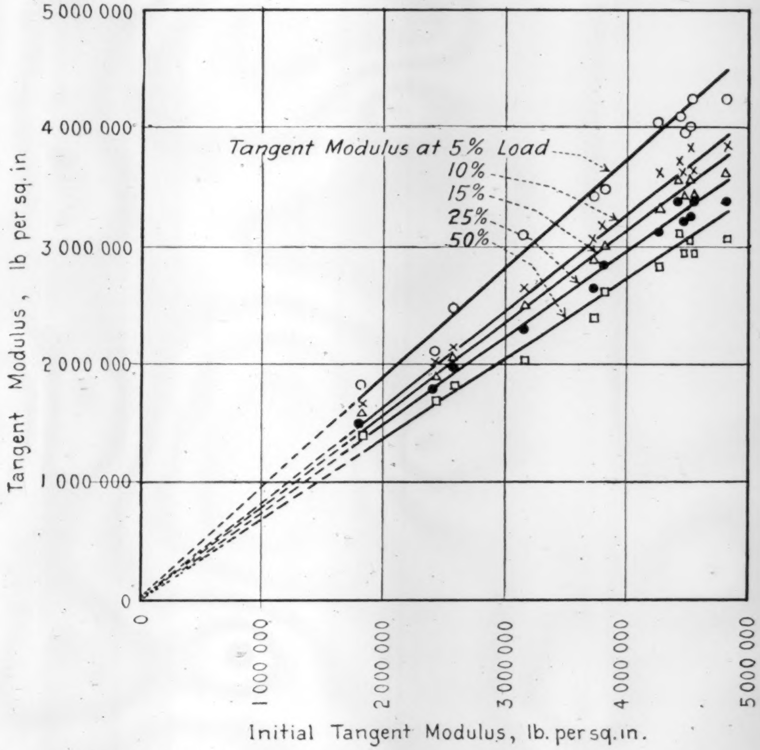

FIG. 34.—Relation of "Initial Tangent" to "Tangent" Modulus.

Data from Table XIII.
28-day compression tests of 6 by 12-in. cylinders.
Each value is the average of 40 tests from 8 mixtures.
Compare Fig. 35.

Data in Table XII show the initial tangent modulus to be equal to the secant modulus at about 10 to 15 per cent of the load.

Fig. 36 shows the tangent modulus of elasticity platted against percentage of ultimate strength for the tests given in Table XII. The ratios of the different measures of modulus of elasticity to each other for other data herein reported differ somewhat from those obtained from Figs. 34 to 36, but the general relation is the same.

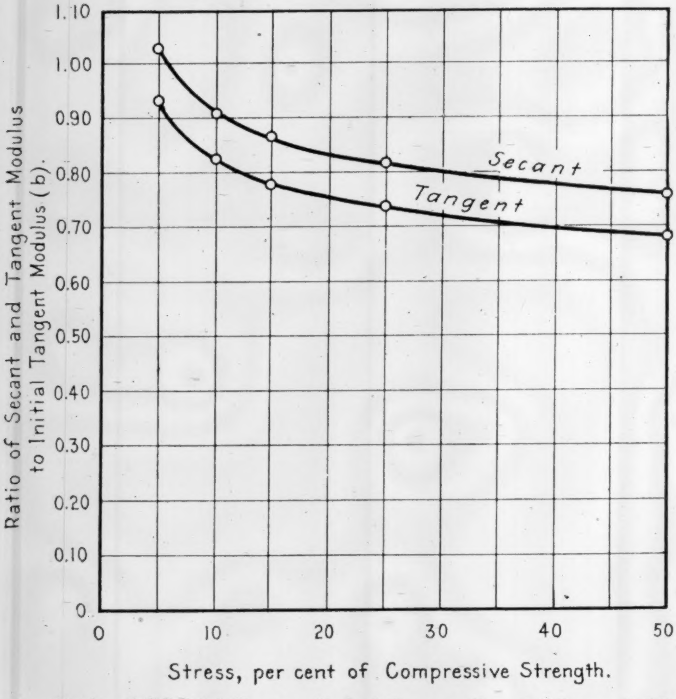

FIG. 35.—Ratio of "Initial Tangent" to "Tangent" and "Secant" Moduli at Different Percentages of the Load.

Data from Table XIII.

NOMOGRAPHIC CHART SHOWING THE INTER-RELATION OF STRENGTH, MODULUS OF ELASTICITY AND COMPOSITION OF CONCRETE.

Knowing the inter-relation of mix, grading, strength, consistency, and the various measures of modulus of elasticity, we are able to construct a nomographic chart on which these variables are represented (Fig. 37). The data from Table XIII were selected as the basis of the chart, since it is for this series only that all of the following variables are represented:

1. Amount of cement (mix);
2. Size and grading of aggregate (fineness modulus);
3. Amount of mixing water (consistency);
4. Compressive strength at 28 days;

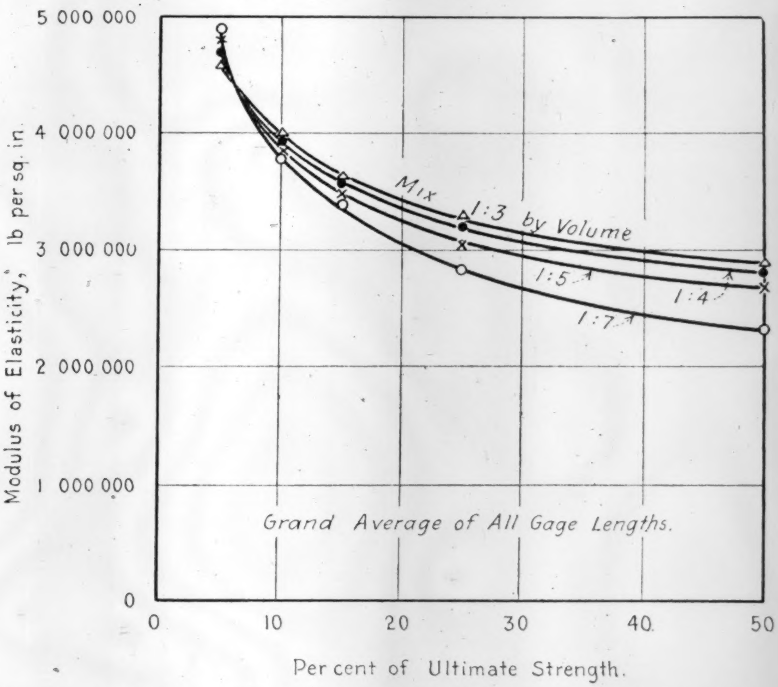

FIG. 36.—Variation of Modulus of Elasticity with Stress at which it is Measured.

Data from Table XII.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in
Relative consistency 1.00.
Each value is the average of 80 tests made on 20 days

5. Initial tangent modulus;
6. Tangent modulus at 5 to 50 per cent of the ultimate load;
7. Secant modulus at 5 to 50 per cent of the ultimate load.

If items 1, 2 and 3 are known we are able to solve for items 4, 5, 6 and 7. If any one of the four items 4, 5, 6 and 7 is known

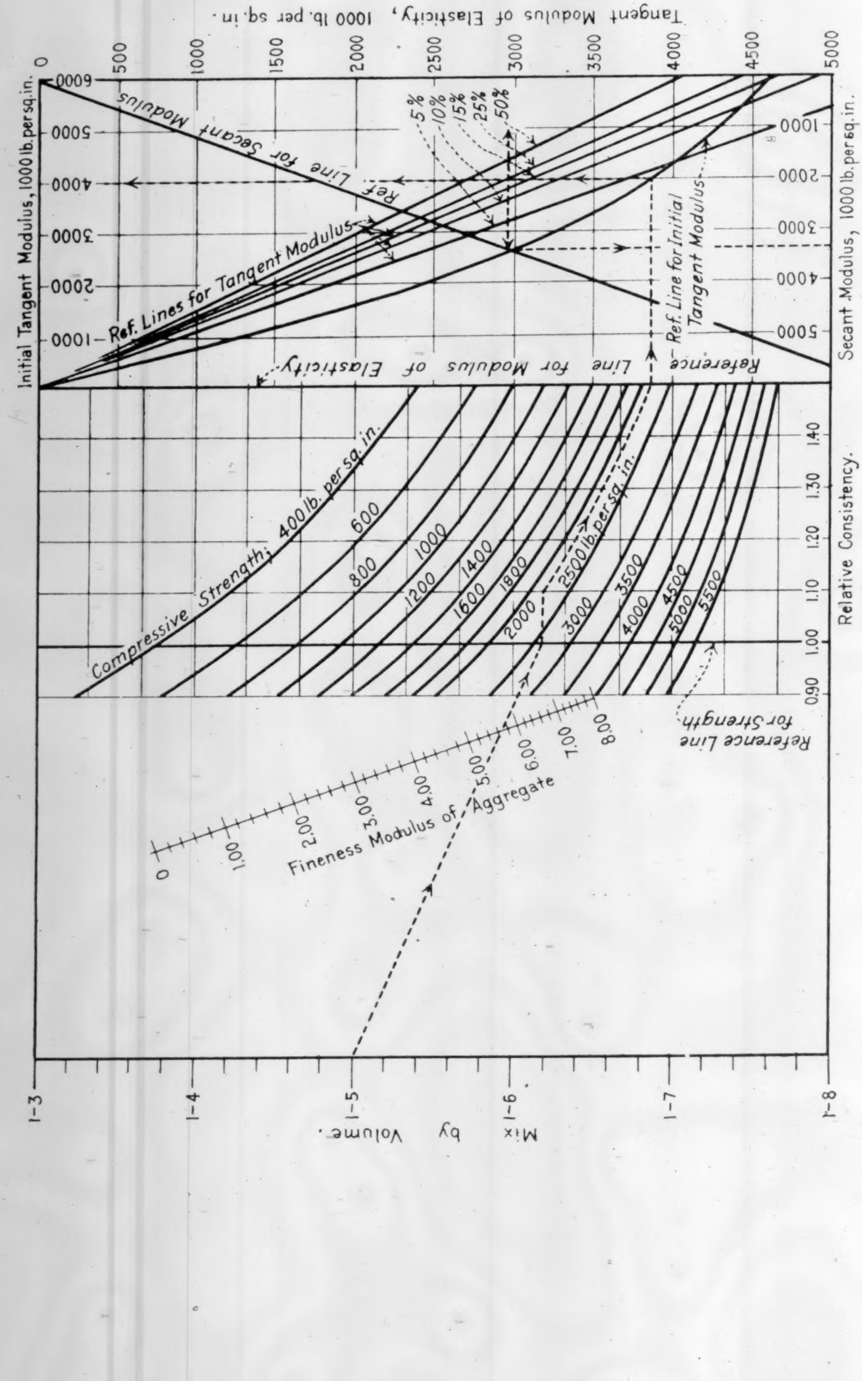

FIG. 37.—Nomographic Chart Showing the Inter-Relation of Proportions of Concrete, Strength and Modulus of Elasticity. Data from Table XIII. Based on 28-day compression tests of 6 by 12-in. cylinders. Sand and pebble aggregate.

the other three can be computed. In using this chart it should be borne in mind that it is based on one series of tests for which the concrete was mixed and cured under laboratory conditions. While it is realized that for a given mix, grading, and consistency, the strengths obtained in practice will be different, it is believed that the relation of modulus of elasticity to strength will be approximately the same as given by the diagram.

Example of Use of Nomographic Chart.—Assume a mix of 1:5; 0–1½-in. aggregate, having a fineness modulus of 5.75; relative consistency 1.10.

1. Draw a straight line through the points representing the mix and the grading of the aggregate to the reference line for strength.
2. From this point draw a horizontal line to the line representing 1.10 relative consistency. This intersection gives the compressive strength at 28 days (2200 lb. per sq. in.).
3. Follow the strength contour to the reference line for modulus of elasticity.
4. Draw a horizontal line to the reference line for initial tangent modulus. Vertically above this the initial tangent modulus (4,000,000 lb. per sq. in.) can be read.
5. To obtain the tangent modulus at, say, 25 per cent of the compressive strength, draw a vertical line from the point on the initial tangent curve to the reference line for tangent modulus marked 25 per cent. The tangent modulus (2,900,000 lb. per sq. in.) is then read on the ordinate at the right.
6. If the secant modulus at 25 per cent load is desired, draw a horizontal line from the point on the 25-per-cent tangent modulus line until it intersects the reference lines for secant modulus. The secant modulus (3,300,000 lb. per sq. in.) is read on the bottom scale.

FURTHER DISCUSSION OF STRESS-DEFORMATION RELATION.

For the data used in the construction of the nomographic chart described above it was shown that the average value of n in Eq. 1 is 0.90. If the compressive strength is assumed and the corresponding secant modulus (E_s) is determined from the nomographic chart (Fig. 37), d can be calculated from Eq. 6. Then by substitution in Eq. 1, K can be computed. In like manner, K can be computed for any compressive strength. The relation of K to compressive strength obtained in this way may be expressed by the equation,

$$K = 29{,}000\ S^{\frac{1}{2}} \dots\dots\dots\dots (17)$$

Average values of modulus of elasticity from Fig. 37, and values of K calculated from Eqs. 1 and 6 are given in Table XVII.

UNIFORMITY OF TESTS.

Consistent values of modulus of elasticity cannot be obtained with as few tests as compressive strength. Where the moduli of elasticity are the average of only 5 tests, they are much more erratic than the average strengths for a like number of tests. In cases where the modulus of elasticity is the average of 10 or more tests the values are very consistent.

Modulus of elasticity values of concrete are erratic because of the non-homogeneity of the material, and because of the difficulty in obtaining accurate stress-deformation data. The initial tangent moduli are particularly erratic because of the variations which may easily result in constructing the tangent. Platting the stress-deformation points on logarithmic coordinates reduces the error in locating the curve and avoids the necessity of constructing a tangent.

Mean errors were calculated for the strengths, initial tangent moduli, and tangent moduli for the tests given in Table XII. In this table each value is the average of 20 tests made on different days. The mean error of the strength tests is 10.2 per cent; of the initial tangent modulus, 22.4 per cent; and of the tangent modulus at 25 per cent of the compressive strength, 15.1 per cent. This indicates that the moduli of elasticity calculated from the logarithmic curve (tangent modulus at 25 per cent load) are considerably more uniform than those calculated from the ordinary stress-deformation curve (initial tangent modulus).

It appears that the modulus of elasticity should be the average of 10 or more tests in order to secure concordant results.

YIELD POINT OF CONCRETE.

Mills[1] states, "Concrete shows a permanent set under the smallest loads. There can therefore be no elastic limit in the true sense of the term. There appears to be a stress, however, below which repetition of the same load does not cause appreciable increase in set, while beyond this stress repetition of load causes increased set indefinitely, finally resulting in rupture far below the normal ultimate strength. For practical purposes, therefore, it is convenient to consider this stress as the elastic limit. Experiments made by Bach, Van Ornum,[2] and others, seem to place this stress at about 50 to 60 per cent of the ultimate strength."

The Bureau of Standards[3] gives values of "yield point" of concrete ranging from about 25 to 50 per cent of the ultimate strength. The method of determining the "yield point" is not given. However, from Hool and Johnson's[4] discussion of these tests it is inferred that the "point where the deviation from a practically straight line relation between stress and strain is first perceived is designated the *yield point*."

In the true sense of the word there is no elastic limit for concrete. There is no basis for determining what may be called the elastic limit or "yield point." The method of determination by repeated loading is much too cumbersome for the ordinary tests.

Our tests show that the stress-deformation relation for concrete follows a definite law up to a certain point. Investigation of data from various sources shows this law to apply for numerous materials. The stress-deformation relation of a perfectly elastic body within the elastic limit is of the same form as that given for concrete and other materials, represented by Eq. 1. For a perfectly elastic material n would equal 1, and K would be the modulus of elasticity. It will be seen at once that the point where this law no longer holds is the elastic limit as defined in the usual manner.

For materials that are not perfectly elastic the above law differs only in that n is not equal to 1 (less than 1 for most materials) and that K is the secant modulus at a unit deformation of 1.

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[1] "Materials of Construction."

[2] *Transactions*, Am. Soc. Civil Engrs., June, 1907.

[3] "*Technologic Paper No. 58*," Bureau of Standards, 1916.

[4] Hool and Johnson, "Concrete Engineers' Handbook."

As in the case of the perfectly elastic material there is a point beyond which this law no longer holds. It would, therefore, seem that this equation furnishes a method for the determination for all materials of what may be called the "yield point." As has been stated it was not our general custom to take measurements at sufficiently small intervals for loads high enough to determine this point for our tests. In a few instances, however, readings were taken at short intervals for the higher loads and the points beyond which the stress-deformation curve of concrete no longer follows the law expressed in Eq. 1 determined. These are the "yield points," as defined above. The values varied from 50 to 90 per cent of the ultimate load.

CONCLUSIONS.

The modulus of elasticity of any material is the ratio of an increment of stress to a corresponding increment of deformation. The stress-deformation relation of concrete is represented by a curve and, consequently, the modulus of elasticity varies, depending on the point on the curve at which it is measured, becoming less for the higher stresses.

Data for three measures of modulus of elasticity are presented as follows:

"Initial tangent" modulus (E_i);
"Tangent" modulus at stresses from 5 to 50 per cent of the compressive strength (E_t);
"Secant" modulus to stresses from 5 to 50 per cent of the compressive strength (E_s).

The initial tangent modulus and the tangent modulus at 25 per cent of the compressive strength are treated in detail. The values for initial tangent modulus were given prominence because of their general use. Obviously the relation for all values of secant and tangent modulus could not be shown. The tangent modulus at 25 per cent of the compressive strength was selected as representative. The inter-relation of the various measures is shown.

A study of the data contained in this report seems to warrant the following conclusions:

1. The relation of compressive stress to deformation for concrete may be represented by the equation:

$$s = Kd^n \quad \text{......................} \quad (1)$$

where s = unit stress of concrete, d = unit deformation of concrete, K = a constant which depends on the strength of the concrete, n = an exponent, approximately constant. The curve represented by this equation has a decreasing slope, and gives decreasing values of modulus of elasticity as the stress is increased.

2. The modulus of elasticity of the concrete is a function of the compressive strength. The relation between modulus of elasticity and strength for mixtures leaner than about 1:3 may be represented by an equation of the form,

$$E = CS^m \quad \text{......................} \quad (8)$$

where E = modulus of elasticity of concrete, C = a constant depending on the conditions of the tests, S = compressive strength of concrete, m = an exponent.

For the initial tangent modulus the average of our tests may be expressed by the equation,

$$E_i = 33{,}000\ S^{\frac{5}{8}} \quad \text{..................} \quad (13)$$

For the tangent modulus at 25 per cent of the compressive strength the equation becomes,

$$E_{t25} = 66{,}000\ S^{\frac{1}{2}} \quad \text{..................} \quad (14)$$

The ratio of modulus of elasticity to strength as shown by these equations varies from about 3300 for the initial tangent for 500-lb. per sq. in. concrete, to 1400 for 5000-lb. concrete; the corresponding values for the tangent modulus at 25 per cent of the compressive strength are about 3000 to 940, respectively.

3. A study of the different variables affecting the strength and modulus of elasticity of concrete further emphasizes the relation shown in Eq. 8.

(*a*) Both the modulus of elasticity and strength increase within certain limits as the aggregate becomes coarser, although the modulus of elasticity increases less rapidly than the strength.

(*b*) An increase in the quantity of cement in the batch causes an increase in values of modulus of elasticity and strength. The modulus of elasticity is affected somewhat less by change in the cement content than the strength.

(*c*) The quantity of mixing water exerts a most marked effect on the modulus of elasticity and strength. An addition of 25 per cent of water to a mixture of normal consistency decreases the modulus of elasticity about 15 to 20 per cent, and the strength about 35 to 40 per cent.

(*d*) Both the modulus of elasticity and strength increase with the age of the concrete, so long as the specimens are kept moist during curing. The strength increases in proportion to the logarithms of the age. The modulus of elasticity follows approximately the same relation.

(*e*) There is no marked difference in the modulus of elasticity and strength of concrete made from high-grade pebbles, crushed limestone, crushed granite or blast furnace slag.

(*f*) A comparison of specimens stored 14 days in damp sand and 77 days in air with specimens stored 91 days in damp sand shows that both the modulus of elasticity and strength are higher for the damp sand storage.

(*g*) Tests for mixing times ranging from ¼ to 10 minutes show both the modulus of elasticity and strength to be greater for the longer mixing times.

4. The secant and tangent moduli of elasticity are less for the higher loads. At a given percentage of the strength these values vary approximately in direct proportion to initial tangent modulus for concrete of ordinary strengths.

5. Deformations measured over gage lengths ranging from 4 to 10 in. on a 6 by 12-in. cylinder show that the gage length exerts only a slight influence on the modulus of elasticity.

6. The inter-relation of modulus of elasticity to strength and the proportions of the concrete is sufficiently definite to make possible the construction of a nomographic chart. While the absolute values given on this diagram cannot be taken to

be representative of concrete made under all conditions, it gives values which stand in the proper relation to each other.

7. A study of the stress-deformation data for a great number of materials, including woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds, indicates that the relation expressed by Eq. 1 is applicable to all materials.

8. A study of the action of the two extensometers used for these tests showed that the Ames dial gave much more uniform results than the Johnson wire-wound dial.

9. Values of modulus of elasticity should be the average of 10 or more tests in order to secure concordant results.

10. The point where the law expressed by Eq. 1 no longer holds is approximately the same as that called the "yield point" of concrete by certain writers. Values of "yield point" obtained in this way varied from 50 to 90 per cent of the compressive strength.

DISCUSSION.

Mr. Talbot. Mr. A. N. Talbot.—I wish to ask if Mr. Walker has a record of the deformations obtained at or near the ultimate strength of the concrete for these various mixes? Such results would be of value in questions relating to reinforced concrete. If he has, it might be well to add to his valuable paper a few results giving the range of the ultimate deformations.

Mr. Walker. Mr. Stanton Walker.—We did not take readings at the ultimate load on most of our specimens. There were two reasons for this: first, the dial is too delicate to leave on the instrument until failure of the specimen, and second, for our purposes we did not consider the data for the higher loads worth the expense that would have been incurred due to the additional time necessary for reading the deformations. We did, however, take readings as near the ultimate load as possible on about 200 or 300 specimens. These data are reported in the paper for 5 tests selected at random from those available. We were not able to find that the stress-deformation relation follows any law beyond 50 to 90 per cent of the ultimate load.

Mr. Hollister. Mr. S. C. Hollister (*by letter*).—There are three points which, in the writer's opinion, should be very carefully considered before the conclusions to which Mr. Walker's paper would lead are accepted. One of these relates to possible causes of the curvatures which the author claims exist in the stress-deformation curve near the origin; the second refers to elastic properties in general, with particular reference to concrete; and the third relates to the application of the author's theory of stress-deformation of concrete to the distribution of stress in a reinforced concrete beam. These will be discussed separately and in the order given.

1. *Relating to the Curvature near the Origin of the Author's Stress-Strain Diagrams.*—The typical stress-deformation curves for concrete, which the author shows in his Fig. 3, have a noticeable curvature in them near the origin. The author assumes that the values obtained are correct if they conform to a curve,

Mr. Hollister. and proceeds to determine the mathematical expression for that curve. The cause of the curvature does not seem to have been investigated, but rather it has been taken to be an elastic characteristic of the material under test. Before this equation can be applied to the concrete stress-deformation curves shown in his Fig. 3, it is necessary first to establish whether or not the experimental data for small loads are representative of the material. He goes on further to say that the equation given satisfies all materials, when proper exponents and constants are chosen. For instance, the stress-strain relation of a perfectly elastic material is a straight line. Eq. 1 becomes a straight line when the exponent n is made unity. But when this is done the equation is no longer of the exponential form, but of the common form of a straight line. The writer notes, for example, that the equation

$$y = \frac{-b\,(a+x)\,x^n}{(a-x)},$$

by choosing proper values for a and b, can be converted into a straight-line equation. Similarly, the equation of an inclined ellipse, one end of whose minor axis terminates at the origin, becomes a straight-line form when the major axis is of infinite length. The writer sees no greater absurdity in choosing either of these equations to represent the stress-deformation relation of a perfectly elastic material than in selecting the author's Eq. 1, yet with proper constants they satisfy the straight-line relation equally well.

In the writer's opinion, the observations of deformation at the early loads are extremely difficult to take accurately. For example, the writer submits a graph of observations (see Fig. 1) taken on a cylinder in a laboratory of the Emergency Fleet Corporation, Concrete Ship Section. The compressometer used is known as the Berry Compressometer, and consists in general of two 6-in. Berry strain gages, with an automatic self-averaging lever system, leading to an Ames dial. This instrument is so graduated as to read a unit deformation of 0.000167 in., with a possibility of interpolation of a tenth of that amount. Because the initial reading on the dial was set to zero with a small load on the cylinder, all of the values plotted in the diagram have

Mr. Hollister. been corrected to zero deformation at zero stress. The loading of the cylinder began at point *A* on the curve, with intervals of at least one minute at each point of observation. At about 400 lb. per sq. in. compression, the points of observation fall along a straight line *RS* to a unit stress of 2600 lb. per sq. in., where the elastic limit is reached. The loads were continued to *B* on the curve, after which the compression was gradually released to the point *E*, where the compressometer was removed from the cylinder, but was then reclamped without disturbing, and the dial set on the same reading as was previously observed at *E*. The removal of the load was then continued as before, until point *C* was reached. The compressometer was again removed, but replaced with the dial set on the reading previously obtained at *D*. The compression was then increased in the same increments as before, until point *F* was reached, where the instrument was again removed and reset on the reading previously obtained at that point. The load was once more increased until the point *G* was reached, where the compression was gradually released to *M*, and then slowly applied to *N*. As stated before, at each intermediate observation, an internal of at least one minute was allowed between applications of load.

A significant feature of this set of observations is that at whatever the unit stress on the cylinder when the compressometer is clamped to the cylinder and the load is advanced, the observations follow along a curved line. If this curve can be carried to a sufficiently large value of compressive stress before the elastic limit is reached, the curve will gradually develop into a straight line. A second feature is that for the particular instrument in question on an increase of load, a curvature concave downward will be at once observed, and that on a decrease of loading the instrument may or may not show at once a curve convex upward.

The phenomena displayed in Fig. 1 have been observed on a number of other occasions by the writer, and with other instruments, and are believed to indicate that great reliance should not be placed in the early observations made on a concrete cylinder, on account of instrumental error, through the adjustment of the instrument to the specimens and the removal of lag in the moving parts.

Mr. Hollister. The writer has, on several occasions, after eliminating error due to backlash, obtained readings which advanced from the origin well up on the tangent, as represented in Fig. 1 by the line *DS* and then, on removal of load, obtained a reading at zero stress at *R*. This also would indicate an inaccuracy in the early readings of the compressive test.

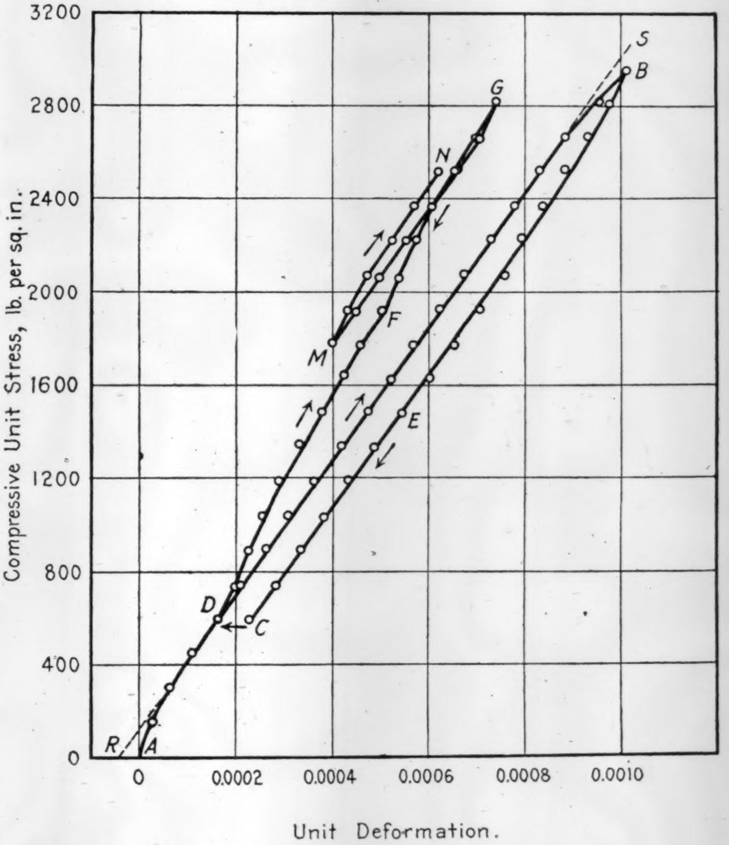

FIG. 1.

The instrument used is of such form that when clamped in place the weight of the instrument is supported on the contact points, which in this case will produce a greater error in increasing readings than in decreasing readings of deformation.

Mr. Hollister. In reviewing the foregoing discussion, it should be recalled that the author claims that the true characteristics of concrete as a material are the small curvatures obtained at the early readings during compression tests. It is believed, therefore, that before Eq. 1 can be accepted it must be established without question that the small curvature obtained in a large majority of the author's test—and for that matter, in a large percentage of similar tests made by other investigators—is not an instrumental error, but a characteristic of the material. The theory should further explain the reason why, in the cylinder whose graph is shown in Fig. 1, a curve was obtained from D to F, rather than a retracing of the line from D to B; and further, why a similar curvature was observed from F to G, rather than a straight line extending from F parallel to the curve DB. Because the curves of these observations, when plotted on logarithmic paper, fall along a straight line and thereby can be expressed by an equation of the form of Eq. 1, does not, in the writer's opinion, justify calling the phenomenon a characteristic of the material.

2. *Discussion of Elastic Properties in General.*—The writer finds himself unable to accept the definition of the modulus of elasticity which is the basis of the paper under discussion. The author defines the modulus of elasticity as "the ratio of an increment of stress to a corresponding increment of deformation." He further states that "this definition is general for all materials, whether or not they are perfectly elastic"; and that "in this sense only perfectly elastic materials have a constant modulus of elasticity." Such a viewpoint the writer believes to be fallacious. A different significance is suggested regarding the modulus of elasticity, which is believed fundamental to the interpretation of the test results upon which the author bases his conclusions.

An *elastic deformation* is one which will entirely disappear when the stress causing it is removed. A modulus is a measure; and the modulus of elasticity is the measure of elasticity possessed by the given material. The material possesses elasticity when it is capable of deforming elastically under stress. Thus, the modulus of elasticity, in the writer's opinion, is the ratio of an increment of stress to the corresponding increment of *elastic* deformation.

Mr. Hollister.

Consider a stress-deformation diagram of the form shown in Fig. 2. A line tangent to the stress-deformation curve *OP* at the origin *O* is the initial tangent modulus, or initial modulus, of elasticity. Assume that the stress is advanced to some point, *P*, well up on the curve, and is then gradually released. The stress-deformation relation during release is shown by the line *PQ*. The total deformation *Ob* at the stress *Oa* may be divided into two parts,—that which is recoverable, and hence elastic, as *Qb;* and that which is not recoverable, and hence plastic, as *OQ*.

Suppose, now, that *PQ* is parallel to *OT*, as in the case of many ductile materials. Then the curvature in *OP* is due to the accumulation of plastic deformation; but the rate of recovery of elastic deformation is a constant for the material. The modulus of elasticity, in the opinion of the writer, is therefore a *constant* for such a material.

The slope of the tangent to the curve at *P* is not a measure of elasticity, but the modulus of elasticity at the point may be expressed by the relation

$$\frac{\delta s}{\delta \epsilon}$$

where ϵ is the unit elastic deformation.

Now, in applying the foregoing discussion to the author's paper, there seem at once two important points to consider. First, the form of curve in Fig. 2 is dissimilar to the author's curves in his Fig. 3. Secondly, it is necessary to establish, if possible, the law of parallelism so far as elastic deformation of concrete is concerned.

The typical curves shown by the author in Fig. 3 have a decided curvature near the origin. His Eq. 1 takes this curvature into account, and describes it as concave downward, with decreasing curvature. If this is an elastic relation, the stress-deformation curve below the elastic limit will retrace itself both with increasing and decreasing load. Many tests made by the writer, which had heretofore not seemed to be of sufficient novelty to warrant publishing, indicate that the curve near the origin as shown in the author's Fig. 3 does not retrace itself on release of load, but rather, the points fall along a line parallel to the tangent at the flat portion of the curve, as at *R* on *RS*, Fig. 1. On advance

Mr. Hollister. of load from this point, the tangent *RD* would be retraced. From such experience, the writer is not willing to accept the author's curve at the origin as an elastic characteristic of the material, nor does such a behavior seem rational in the case of a material which exhibits a plasticity which increases with intensity of stress and duration of load application.

F. R. McMillan[1] has pointed out the law of parallelism for concrete under repetition of load. Tests which the writer has made from time to time have exhibited this law consistently.

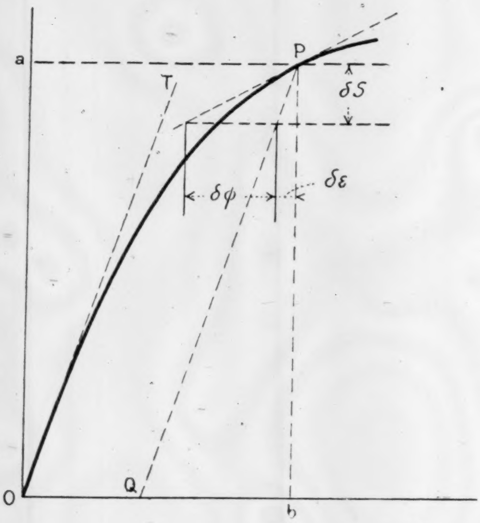

FIG. 2.

Many other materials follow a similar law. If this law is true for a material, then the writer believes that the modulus of elasticity for the material is a constant; and that the only occasion on which the modulus may be considered a variable is that in which the law of parallelism does not hold.

3. *Eq. 1 as applied to Flexure of Reinforced Concrete Beams.*—It is proposed now to apply the conclusions which the author draws concerning the stress-deformation phenomena of concrete to the theory of flexure of a reinforced concrete beam.

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[1] *Proceedings*, Am. Concrete Inst., Vol. XII, p. 314 (1916).

Mr. Hollister.

Before entering into a discussion of the distribution of compressive stress in a reinforced concrete member in flexure, it will be necessary to fix upon some "initial modulus" of elasticity as the author defines it in his paper. In basic Eq. 1, the author asserts that *d* has an exponent less than unity; hence the initial tangent to the curve of the equation at the origin must have infinite slope. The author points this out in his paper, and then proceeds to use an "initial tangent modulus" throughout the greater portion of his paper which has finite value, but he does not explain how this value is obtained. It would appear that since it could not be obtained from Eq. 1, and likewise could not be obtained by a logarithmic graph of the experimental data, it must then have been obtained in some approximate manner, as shown in his Fig. 3. It is not easy to understand what justification the author has for thus shifting from the equation which he offers to express the true relation of stress to deformation, to some modification of present methods of interpreting the relation of stress and strain in concrete, except that it is obvious that the form of equation suggested by the author is not rational in this regard. In order to give a fair interpretation, therefore, to the author's proposed theory of stress-strain relation, a combination of Eq. 1 and his rational "initial tangent modulus" will be used. This will result in a form of curve which follows Eq. 1 with the exception that the initial slope is not infinite but has the finite value represented in the rationally determined "initial tangent modulus."

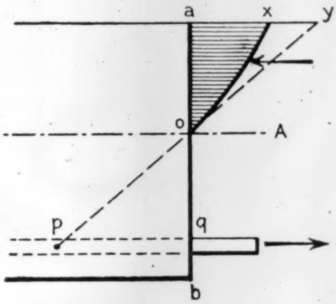

FIG. 3.

Mr. Hollister. Consider now the beam illustrated in Fig. 3. Assuming, as is the general practice in the flexure theory of concrete, that a plane surface is conserved during bending, the line *poy* will be a straight line, and above the neutral axis would represent the state of stress in the concrete if the stress-strain relation was a straight line, equivalent to the initial tangent modulus used by the author. Since the stress-strain relation is a curve, as expressed by Eq. 1, the compressive stresses will be distributed in accordance with the curve *ox*, which has a *decreasing* curvature in moving from *o* to *x*. Let us assume now that the extreme fiber in compression is stressed to one-fourth the ultimate strength of the concrete in compression. This will closely resemble the state of flexure at usual working stresses. The difference between *ax* and *ay* is proportional to the difference between the "initial tangent modulus" and the secant modulus at 25 per cent of the compressive strength, both moduli being in accordance with the author's paper. Thus, the stress distribution in this case would be at considerable variance with the straight-line theory which is commonly employed for computing reinforced concrete beams.

Suppose, now, that the load upon the beam is advanced to the elastic limit of the concrete, as determined in the manner the author suggests. The form of curve shown in Fig. 3 would still hold. However, if the load is advanced beyond that point, well toward the ultimate compressive strength of the concrete, as pointed out by the author, the upper portion of the curve no longer follows Eq. 1, but now takes on a new form, as represented by the curvature of the stress-deformation diagram for this concrete in compression. We would then have a curve with a greater curvature at both ends than near the middle.

If we were to confine ourselves strictly to the stress-strain relation expressed in Eq. 1, the form of the curve *ox* would be parabolic with the vertex at the neutral axis and would thus be tangent to the neutral axis. Such a proposition would, of course, be an absurdity.

Mr. Williams. MR. G. M. WILLIAMS (*by letter*).—Since the modulus of elasticity of concrete is one of the important factors in the design of reinforced concrete members, it is very essential that the true value of this property be known. Whatever assumptions

Mr. Williams.

or methods of analyses of the stress-deformation curve be employed to derive this value, the deformation in practice has some fixed and definite relation to the applied load, and if the true relations between stress and strain are disregarded incorrect values for the modulus are certain to follow.

The determination of the value of the modulus may be divided into two steps: first, the application of load to some form of concrete test specimen, usually a cylinder whose height is twice the diameter, together with measurement of the deformation within some fixed gage length for each increment of load; and second, the analysis of the results so obtained. For accuracy in determining the true modulus of elasticity it is necessary that appreciable instrumental errors be eliminated and that the stress-strain relation observed be the true relation for the material for repeated applications of loads as occur in practice, and that the results so obtained be properly analyzed.

The test data and discussion of results given in Mr. Walker's paper apparently bear out the assumptions and conclusions of many investigators in the past, that the stress-strain relation for concrete is not linear but is represented by a curve of the type $s = Kd^n$ where s = unit stress in concrete, d = unit deformation, K = constant depending upon strength and n = an approximately constant exponent, and that various values can be obtained for E depending upon the method of analysis such as the "Initial Tangent," "Tangent," and "Secant" or "Chord" method.

The belief that the stress-strain relation is represented by a curve such as the above is not justified for stresses below and well above those used in concrete design. Repeated loading tests on the same specimens show that the relation is linear and as well defined and constant for any particular specimen as is the stress-strain relation of steel. The fact that most stress-strain curves are obtained by single sets of readings up to the yield point of concrete has resulted in a general misunderstanding of the true relation for this material. During the first application of loads after applying the deformeter, readings obtained for loads of less than 500 or 600 lb. per sq. in. are often erratic, as indicated by more consistent readings which are obtained with further loading. These inaccurate values are probably due for the most part to instrumental errors which are eliminated in later trials

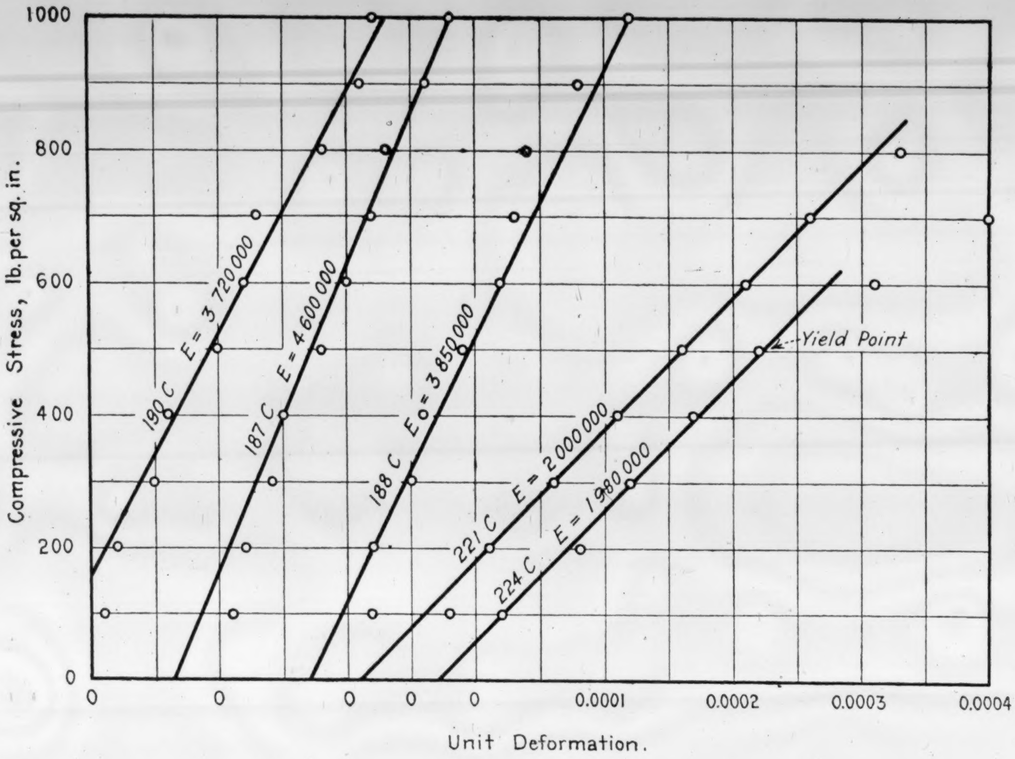

FIG. 4.—Modulus of Elasticity of Concrete by the Straight-Line Method. Data from Walker's Table III.

Mr. Williams.

by the instrument automatically adjusting itself during the first application of loads. If the deformeter is removed and then replaced the readings for the first loading will often show similar inaccuracies.

However, if care is used in adjusting the instrument and in centering the test piece, the value for modulus from later trials may be very closely approximated from the results of the first loading, as is referred to later, thereby avoiding the expenditure of the large amount of extra time and labor involved in repeated loading tests.

Reference to Fig. 4 shows the data given in Table III of Mr. Walker's paper, in diagrammatic form, for loads up to 800 and 1000 lb. per sq. in. The modulus is shown as determined by the straight-line method, which assumes that the stress-strain relation for concrete below the yield point is linear. The greatest errors in the readings for the first loadings will be found for the small deformations, so that these points should be given little consideration in drawing the line which approximates the plotted points. For specimen 190 C and 188 C, owing to the apparent errors in deformation shown even for the high loadings,—due probably to a combination of short gage length and type of instrument used,—it is rather difficult to draw a line which will properly average the plotted points; but some assistance is given by consideration of deformations for loads beyond those shown on the diagram. No doubt a second application of the series of loads to each would have resulted in points which would more clearly show the true straight line relation with perhaps a slightly different slope for the line.

The values for *E* as derived by the straight line method, and as given for "Initial Tangent" by Mr. Walker, are as follows:

	STRAIGHT LINE METHOD.	WALKER, INITIAL TANGENT METHOD.
190 C	3 720 000	4 630 000
187 C	4 600 000	6 000 000
188 C	3 850 000	5 840 000
221 C	2 000 000	2 500 000
224 C	1 980 000	2 000 000

The results of repeated loading tests on several different 8 by 16-in. test specimens selected at random from a lot in storage

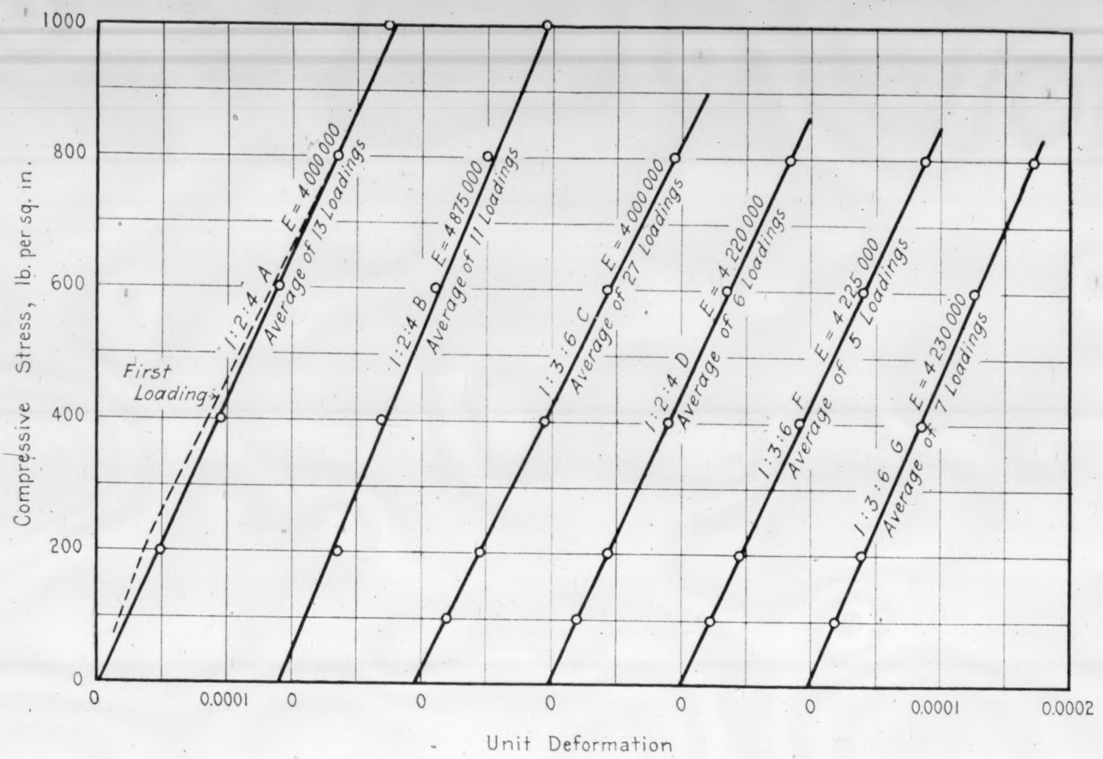

FIG. 5.—Modulus of Elasticity of Concrete by the Straight-Line Method. Typical Stress-Strain Curve.

Mr. Williams. at the Bureau of Standards are shown in Fig. 5. With the exception of specimen A, the variation between deformations for first and the subsequent loadings is too small to be represented on the drawing. It is seen that the stress-strain curve is in all cases essentially a straight line for the first as well as later loadings. The data given in Table I for specimen G is typical of that obtained for the other specimens.

TABLE I.—STRESS-STRAIN DATA FOR SPECIMEN G, FIG. 5.

No. of Loading	Unit Deformation for given Loads (lb. per sq. in.).				
	100	200	400	600	800
1	0.000019	0.000040	0.000080	0.000128	0.000174
2	0.000019	0.000041	0.000086	0.000127	0.000171
3	......	0.000041	0.000085	0.000127	0.000171
4	......	......	......	......	0.000172
5	......	......	......	......	0.000172
6	0.000019	0.000039	0.000085	0.000128	0.000172
7	......	......	......	......	0.000172

A greater number of repetitions of the loadings would have probably shown greater variations than the above, especially for the smaller stresses; but it is clearly seen that no logarithmic curves or exponential equations are needed to express the true relation between stress and deformation of concrete.

TABLE II.—MODULUS OF ELASTICITY OF CONCRETE.

Cylinder, 8 by 16 in. 1:2:4 Concrete. Age, 2 and 7 years.

Results of deformation readings under repeated loadings for both wet and dry condition.

Age, years.		Unit Deformation at given Loads (lb. per sq. in.).					
		100	200	400	600	800	1000
2	Maximum	0.000033	0.000071	0.000138	0.000200	0.000262	......
	Minimum	0.000017	0.000054	0.000117	0.000175	0.000221	......
	Average	0.000027	0.000062	0.000127	0.000188	0.000246	......
	No. of Loadings	14	14	14	14	14	......
7	Maximum	......	0.000067	0.000129	0.000186	0.000239	0.000298
	Minimum	......	0.000041	0.000096	0.000164	0.000221	0.000286
	Average	......	0.000058	0.000118	0.000176	0.000232	0.000290
	No. of loadings	......	36	34	34	150	7

In Table II are shown the data obtained by repeatedly applying loads to a test specimen when dry and when saturated.

Mr. Williams. This 8 by 16-in. cylinder of 1:2:4 concrete was first placed in the testing machine in 1914 when two years old. The results shown for this period represent the average deformations for fourteen separate applications of stress from 0 to 800 lb. per sq. in. After the eighth loading the deformeter was removed and the cylinder placed in water. After two days immersion it was again placed in the machine and the remaining readings taken at intervals during three days while drying.

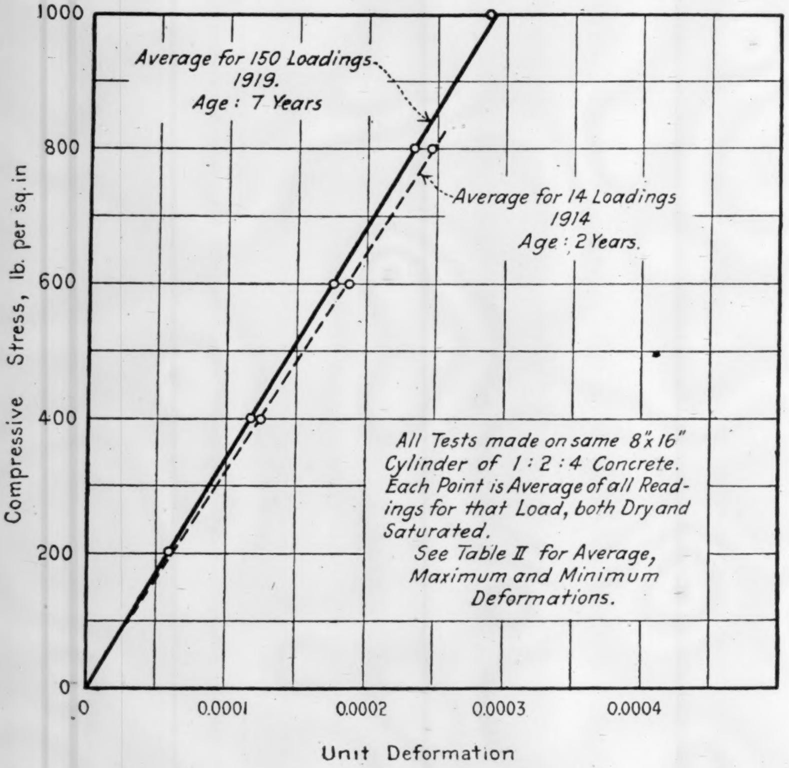

FIG. 6.—Modulus of Elasticity of Concrete by the Straight-Line Method. Averages of Repeated Loadings on the Same Specimen at Ages of Two and Seven Years.

No appreciable difference in results was noted for the saturated and dry condition. In 1919, at the age of seven years,

Mr. Williams. the same cylinder was again treated in the same manner. The load of 800 lb. per sq. in. was applied a total of more than 150 times at intervals during a period of several days with occasional readings taken for all loadings up to and including 1000 lb. per sq. in. Again no difference was found between dry and saturated conditions of the concrete. During the five years the modulus of elasticity increased slightly from 3,250,000 to 3,450,000. The average of the results are shown in Fig. 6.

The straight-line method of determining the modulus of elasticity of concrete was used for the values shown in *Technologic Paper No. 58* of the Bureau of Standards. No doubt more accurate values for E would have been obtained had a preliminary load of about 1000 lb. per sq. in., more or less, been applied before taking the deformation readings; but in most cases the straight-line relation between stress and strain was very apparent and the values so obtained more nearly represent the true modulus than those which would have resulted from the use of the initial tangent, tangent or chord methods. The term "yield point" was used to describe the load at which deformation is no longer directly proportional to the stress. This point will be clearly defined and apparent when errors due to readings taken during first loading are eliminated. In Fig. 4 the yield point for specimen 224 C is shown at 500 lb. per sq. in.

It would appear that if proper consideration is given to the results of tests which clearly indicate that for all practical purposes concrete is a perfectly elastic material, most of the mystery veiling the modulus of elasticity of the material and its proper determination will be removed and such terms as initial modulus, chord modulus, secant modulus, etc., which bear no relation to the elastic properties of concrete, may be forgotten.

Mr. Walker. MR. WALKER (*Author's closure by letter*).—The writer feels that the principal value of the data presented in this report lies in the following:

1. The determination of the modulus of elasticity of concrete of different mixes, consistencies, sizes and gradings of aggregate, ages, etc.;
2. The determination of the relation of the modulus of elasticity to the compressive strength of concrete;
3. The tests confirm the work of earlier investigations in

Mr. Walker. showing that the stress-deformation relation for concrete in compression can be represented by an equation of the exponential form (Eq. 1);

4. A mass of data on the strength and other properties of concrete is given which will be of value entirely aside from considerations of modulus of elasticity.

It is not clear why Mr. Hollister objects to the form of equation used to represent the stress-deformation relation for concrete. It is apparent that equations of many different forms may be used. This being true, the simplest type which is of general application should be chosen. The exponential form expressed by Eq. 1 lends itself to this use, since the constants may be easily determined. The fact that for a certain value for the exponent the equation represents a straight line does not change the exponential form of the equation, but simply shows that the straight line is a special case in the family of exponential curves. No originality is claimed in using the exponential equation, since it was pointed out in the paper that equations of this form were used by Bach many years ago.

Our examination of the first equation cited by Mr. Hollister shows that it becomes a straight line *only* when $a=0$ and $n=1$, in which case it becomes our Eq. 1. The absurdity would seem to lie in the proposal to use expressions of complex form, when an equation of simple form can be used.

The writer will not attempt to explain the peculiar relations found in Mr. Hollister's Fig. 1. It is difficult to draw general conclusions from the results of a single test. There would seem to be many objections to an attempt to generalize on the properties of concrete from observations made on a cylinder after it had been loaded beyond its elastic limit. We have studied the results of tests on many concrete specimens which were loaded repeatedly, but have not heretofore observed relations similar to those in Mr. Hollister's Fig. 1. Repeated load tests of concrete generally show a "hysteresis effect" resulting from a certain lag in the deformation with reference to the stress; a phenomenon which is observed also in studying the deflection of reinforced concrete beams under repeated loading.

The writer is aware of the difficulties in the way of measuring the deformation at early loads, but he does not agree that our

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data are in error on account of lag in the instrument, such as Mr. Hollister suggests. We have carefully observed the behavior of this extensometer at early loads. There is no reason to believe that any of the features of our stress-deformation curves can be attributed to slip of the instrument. The fact that some tests consistently show a curvature at early loads and others show a straight line nearly from the beginning seems sufficient evidence that we secured the true stress-deformation relation and that the curvature is not due to instrumental error. The same instrument was used in determining the modulus of elasticity of steel tubing and showed no evidence of curvature at early loads. Tests were also made on concrete specimens where the extensometer was removed a number of times without release of load. These tests served only to sustain our confidence in the accuracy of the instrument. Parallel tests were made on the same concrete specimens, using the extensometer shown in Fig. 2 and a 6-in. Berry strain gage (not the Berry compressometer referred to by Mr. Hollister). The same results were obtained with both instruments. Had there been appreciable lag in the instrument used it would have given a curve different from the Berry gage, especially at early loads, since it is obvious that in the case of the strain gage conditions were identical for all loads. The actual deformations at the early loads are only of theoretical interest; whatever they are, they have no particular bearing on the use of the information obtained in tests of concrete under working loads and higher stresses. Since the exponential equation of the form given does represent the stress-deformation relation for the range of values which are of importance for design, it does not seem unreasonable to assume that the same law holds for loads below, say, 100 lb. per sq. in.

While it is true that our Eq. 1 represents a curvilinear relation (except where $n=1$), it is probable that Mr. Hollister has overestimated the amount of curvature. Some tests show greater curvature than others, but in no case is the curvature very great, the smallest value of n being about 0.75.

It appears that Mr. Hollister has assumed a purely hypothetical case in his Fig. 2. The writer knows of no "ductile material" which gives the relation shown. We have not recommended the use of the initial tangent modulus; the term "initial

Mr. Walker. tangent" modulus has been used in referring to the modulus of elasticity for low loads simply for the reason that this expression is in general use.

It would be highly desirable to know the elastic properties of concrete after it had been subjected to repeated loadings, but the determination of the values involves so much painstaking work that no one has found it possible to carry out tests from which definite conclusions may be drawn. It seems likely that if the concrete were loaded repeatedly and the modulus of elasticity determined for this condition, the values would bear the same relation to each other as those given in my paper, so far as differences in the make-up of the concrete are concerned. The "law of parallelism," described by Mr. Hollister, has not been generally accepted as applicable for concrete members under load. In the vast majority of reinforced concrete structures it is the first application of load which determines the relation between the stresses carried by the concrete and the steel; for this reason the properties of the concrete at first loading are of importance. Opinion among engineers varies as to whether we are interested in *elastic* deformations or *total* deformations for purposes of design. The actual conditions under which a member in a reinforced concrete building is loaded varies so much with local conditions and differs in so many features from those which may be used in the laboratory that it seems probable that the conditions of these tests are as representative as any.

Mr. Hollister has apparently overlooked the statement in my paper to the effect that the "initial tangent" modulus as determined in the usual manner is equivalent to the modulus of elasticity determined by a secant drawn to loads equal to 5 to 15 per cent of the compressive strength of the concrete. We have suggested the modulus of elasticity at 25 per cent on the ultimate load as a proper value for use in design. As stated above, the term "initial tangent" modulus was used (generally in quotation) since this term is commonly met and its meaning well understood; there is no absurdity involved in applying this term to the modulus of elasticity at low loads, although Eq. 1. suggests an infinite value of modulus of elasticity at the lower limit of stress.

Mr. Hollister's discussion of reinforced concrete beams is

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difficult to follow, since it appears to exhibit a certain confusion of thought. One paragraph begins with a mention of the assumed conservation of plane sections and closes with a reference to the straight-line theory which is commonly used in design. Were it not for the proximity of these statements the writer would not consider it necessary to point out here that there is no relation whatever between the conservation of plane sections and the straight-line theory of stress in a beam. Even if the "law of plane sections" were strictly correct,—which is not true,—that would not indicate that the straight-line method used in beam design is correct. The most elementary analysis will show that the law of plane sections is not strictly correct regardless of the type of beam or the material used, so long as horizontal shear exists. Shearing stresses are generally present in beams under load. This so-called law is a *useful approximation*, but it should not be used as a basis for the discussion of conclusions at variance with it. Mr. Hollister rejects the conclusion that the modulus of elasticity of concrete is infinite at zero load as an absurdity, yet he fails to observe that by *assuming* the conservation of plane sections he is also assuming an *infinite shearing modulus for all loads*. The assumption seems to be the greater absurdity.

The straight-line theory used in reinforced concrete beam design is well recognized as a rough approximation which simplifies analysis and computation and gives values on the safe side. Some text books illustrate probably a dozen different stress-deformation theories which have been used or proposed at different times in the development of the art. The parabolic curve with vertex at the ultimate stress and passing through the origin seems to have met with most favor due to its simple form and to a feeling that the stress-deformation relation thus derived was probably correct. The tests reported in this paper establish the fact that the true stress-deformation relation for concrete in compression can best be represented by a curve having an exponential equation. Special cases may be of linear or nearly parabolic form; however, the position of the curve is entirely different from the parabolic form mentioned above, in that the curvature in general decreases with increased load below the elastic limit. The stress-solid for a reinforced concrete beam would then be bounded by a surface of decreasing curvature

Mr. Walker. which is tangent to the neutral plane, somewhat as shown by Mr. Hollister's Fig. 3. Mr. Hollister characterizes this as an absurdity, but it is exactly the relation shown by all of our tests. The writer knows of no well-established facts, derived either from the theory of reinforced concrete design or from experimental studies of reinforced concrete, that contradict this conclusion.

Many of the points raised by Mr. Williams have been discussed above. Our test data were taken on cylinders in a damp condition. The values shown by Mr. Williams may be correct for specimens which have been stored for long periods in air. Our tests also point to the conclusions that the older specimens approach straight-line stress-deformation relations. It should be borne in mind that practically all designs must be based on the properties of concrete at early ages. It seems doubtful whether an 8 by 16-in. cylinder should be considered saturated after 2 days in water, following 2 years' storage in air. One would expect to find a greater difference between the dry and wet concrete than that shown by Mr. Williams' tests.

Other straight lines may be drawn for test (except 224C) in Mr. Williams' Fig. 4 which more nearly represent the points than the lines given. In every instance the slope would be increased, producing values of modulus of elasticity closely approximating our values for "initial tangent" modulus given in his table.

RELATION BETWEEN METHODS OF CURING STANDARD CONCRETE TEST SPECIMENS AND THEIR COMPRESSIVE STRENGTH AT 28 DAYS.

By Howard W. Green.

SUMMARY.

The effect of exposure to the air upon the compressive strength of concrete has been referred to at different times, but its importance in relation to a proper understanding of the results of a set of compression test specimens or to a clear analysis of a concrete structure is realized by few engineers.

This investigation was undertaken to determine what effect exposure to the drying properties of the air would have upon the compressive strength of concrete test specimens that had been buried in moist sand for different periods of time.

The results obtained show:

1. That the careful curing of concrete test specimens is as important an item, when uniform results are desired, as proportioning the aggregate or mixing the batch;
2. That the variation between specimens cured properly and improperly is often over 100 per cent;
3. That the longer concrete remains moist the higher will be its compressive strength;
4. That the compressive strength of test specimens buried in moist sand may be increased by exposing them to the drying effects of the air.

RELATION BETWEEN METHODS OF CURING STANDARD CONCRETE TEST SPECIMENS AND THEIR COMPRESSIVE STRENGTH AT 28 DAYS.

BY HOWARD W. GREEN.

In the course of ascertaining the effect of various methods of curing cement-concrete pavements in the Canal Zone, an investigation with the following objects in view became necessary:

1. The effect that exposure to the drying properties of the air would have upon the compressive strength of concrete test specimens that had been buried in moist sand for different periods of time;
2. The determination of the number of days that specimens should be allowed to dry after being kept moist and before being broken for the 28-day test.
3. The application of these results to concrete construction work.

The routine testing of specimens of the concrete which is actually being used on the work is coming more and more into general use. It is, therefore, most essential that the methods of making, storing and breaking these specimens be standardized to the smallest detail in order that the results obtained by the different laboratories throughout the country may be of the greatest general value. This Society through one of its committees, C-9 on Concrete and Concrete Aggregates, has suggested specifications for the making of these tests. These suggested methods include the optimum size and shape of the specimen, methods of sampling the concrete, molding the specimens and testing.[1] The committee suggested the following technic for the treatment of concrete cylinders between the time they are made and broken.

> "To prevent the specimen from drying out, it should be covered or otherwise protected. If desired, the mold itself may be buried in sand while the specimen is being molded."

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part I, p. 322 (1917).

> "At the end of 48 hours the specimen should be removed from the mold and buried in damp sand."
>
> "Ten days prior to the date of test, specimens should be well packed in damp sand or wet shavings and shipped to the testing laboratory, where they should be stored either in a moist room or in damp sand until the date of the test."

The specimens tested during the investigation were taken from concrete made with a standard brand of Portland cement, namely, Atlas Portland cement. All of the cement used during this investigation satisfied the physical requirements determined in accordance with the Standard Specifications and Tests for Portland Cement (C 9–17) of this Society. The sand and gravel were of fair quality, with a maximum diameter of 1½ in. The water used was all filtered and of excellent quality.

The specimens consisted of 6 by 12-in. cylinders. These cylinders were made in galvanized iron pipe molds constructed according to the recommendations of Committee C-9.[1]

The methods suggested by this committee for the making and breaking of specimens have been followed throughout this investigation. The molds were buried in moist sand. The specimens were removed from the molds after 24 or 48 hours. It has been found, in the course of making 3000 specimens, that usually the strength of the concrete is not noticeably affected by removing the molds after 24 hours. In two instances, however, the concrete at the end of 48 hours was so soft that it became badly broken by removing the forms and only after several days did it become normal.

The specimens removed from the molds were immediately replaced in the moist sand, where they remained until at the age of 28 days they were taken to the laboratory and broken. The standard specimens were buried in moist sand for the total length of time (type of treatment, A). The other specimens were removed from the moist sand after 1, 3, 5, etc., days at which time they were exposed to the drying properties of the air (type of treatment, A-1, A-3, A-5, etc.).

The 500 cylinders broken were made in series which differed in the following details:

Tables I and II summarize the results of cylinders in the

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[1] *Loc. cit.*

TABLE I.—COMPRESSIVE STRENGTH OF 6 BY 12-IN. CYLINDERS WHEN CURED UNDER STANDARD CONDITIONS (TYPE A), COMPARED WITH STRENGTH WHEN CURED UNDER OTHER CONDITIONS.

TYPE A.—BURIED IN MOIST SAND UNTIL TESTED.
TYPE A-27.—REMOVED FROM THE MOIST SAND STORAGE AND EXPOSED TO THE AIR FOR 27 DAYS, ETC.
ALL CYLINDERS BROKEN AT THE AGE OF 28 DAYS. EACH VALUE IS THE AVERAGE OF 4 CYLINDERS.

Type of Treatment.	Age when Removed from Moist Sand Storage, days.	Series P. R. 61.			Series P. R. 69.			Series P. R. 70.			Series P. R. 72.			Average Ratio of Strength of Special to Type A Cylinders, expressed as per cent.
		Average Compressive Strength, lb. per sq. in.	Reliability, per cent.	Ratio of Strength of Special to Type A Cylinders, expressed as per cent.	Average Compressive Strength, lb. per sq. in.	Reliability, per cent.	Ratio of Strength of Special to Type A Cylinders, expressed as per cent.	Average Compressive Strength, lb. per sq. in.	Reliability, per cent.	Ratio of Strength of Special to Type A Cylinders, expressed as per cent.	Average Compressive Strength, lb. per sq. in.	Reliability, per cent.	Ratio of Strength of Special to Type A Cylinders, expressed as per cent.	
A............	28	1466	2	100.0	2026	2	100.0	1678	5	100.0	1561	4	100.0	100.0
A-27..........	27	1761	5	120.1	2118	2	104.1	1919	7	114.2	1937	4	124.0	115.6
A-25..........	25	1801	5	123.0	2249	5	111.0	2159	4	129.0	2135	7	136.5	124.9
A-23..........	23	1823	6	124.8	2101	3	103.8	2094	4	125.0	1918	4	122.7	119.1
A-21..........	21	1911	3	130.7	2271	4	112.0	2085	3	124.5	2132	5	136.2	125.9
A-19..........	19	....	..	.....	2220	3	109.4	2078	5	123.9	2104	4	135.0	122.8
A-17..........	17	1794	3	122.5	....	..	.....	2114	6	125.9	1920	4	123.0	123.8
A-15..........	15	1810	5	123.5	....	..	.....	2061	5	123.0	2153	5	137.9	128.1
A-13..........	13	1693	5	115.5	2206	3	108.9	....	..	.....	....	..	.....	112.2
A-11..........	11	1799	6	122.8	2029	4	100.1	....	..	.....	....	..	.....	111.5
A-9..........	9	1739	8	118.5	2060	5	101.6	1758	3	104.6	1717	5	109.9	108.7
A-7..........	7	1510	11	103.0	1986	2	97.6	1669	6	99.5	1589	6	101.7	100.5
A-5..........	5	1424	4	97.5	1680	4	82.7	1594	5	95.0	1577	2	101.1	94.1
A-3..........	3	1253	1	85.6	1395	2	68.6	1397	4	83.2	1243	8	79.6	79.3
A-1..........	1	892	5	60.9	928	3	45.6	959	5	57.0	1114	7	71.4	58.7

"Pacific Roads" and "Experimental Mixer" series. The P.R. series was taken from the concrete mixed for road construction. The proportions used in the concrete were equivalent to 1:2:4, by volume. The consistency was mushy or mushy-fluid. The time of mix for P.R. 61, 69, 70, and 72 shown in Table I averaged 60 seconds and was very constant. The time of mix for the P.R. series in Table II was shorter and varied considerably.

TABLE II.—COMPRESSIVE STRENGTH OF 6 BY 12-IN. CYLINDERS WHEN CURED UNDER STANDARD CONDITIONS TYPE (A), COMPARED WITH STRENGTH WHEN CURED UNDER OTHER CONDITIONS.

TYPE A.—BURIED IN MOIST SAND UNTIL TESTED.
TYPE A-27.—REMOVED FROM THE MOIST SAND STORAGE AND EXPOSED TO THE AIR FOR 27 DAYS, ETC.
ALL CYLINDERS BROKEN AT THE AGE OF 28 DAYS. EACH VALUE IS THE AVERAGE OF 4 CYLINDERS.

Type of Treatment.	Age when Removed from Moist Sand Storage, days.	Ratio of Compressive Strength of Special Cylinders to Compressive Strength of Type A Cylinders, expressed as per cent.										
		P.R. 27.	P.R. 43.	P.R. 63.	P.R. 73.	E.M. 2.	E.M. 6.	E.M. 9.	E.M. 10.	E.M. 12.	E.M. 13	E.M. 14.
A	28	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
A-27	27	......	......	93.5	113.0	122.0	......	110.1	......	117.0	......	......
A-26	26	......	......	......	109.6	......	95.8	......	113.3	124.0	......	......
A-25	25	......	120.2	125.1	......	......	......	......	......	......	......	......
A-21	21	......	......	......	......	......	......	......	......	......	......	124.2
A-19	19	......	......	107.3	......	......	......	......	......	......	......	......
A-15	15	......	......	91.5	......	......	......	......	......	......	......	......
A-14	14	......	116.0	......	......	......	......	......	......	......	......	......
A-10	10	......	112.6	......	......	......	......	......	......	......	......	......
A-6	6	......	102.9	......	......	......	......	......	......	......	......	......
A-2	2	74.8	101.2	......	71.0	......	......	......	......	......	67.5	......

The concrete used in the E.M. series, Table II, was made with aggregate from the same source as that for the P.R. series. The aggregate in this series had been sun-dried and divided into seven different sizes. The proportion of the different sized particles was constant throughout this series. The different sized aggregates as well as cement and water were proportioned by weight. The mixes varied from 1:4 to 1:8. The time of mix was constant, 5 minutes, but the consistencies of the different sets varied between wide limits.

Table III summarizes the results of cylinders in the "Ancon Hospital" series which were taken from the concrete placed in the Ancon Hospital construction. Although the proportion was 1:2:4, by volume, the consistency and time of mix varied considerably.

TABLE III.—COMPRESSIVE STRENGTH OF 6 BY 12-IN. CYLINDERS WHEN CURED UNDER STANDARD CONDITIONS (TYPE A), COMPARED WITH STRENGTH WHEN CURED UNDER OTHER CONDITIONS.

TYPE A.—BURIED IN MOIST SAND UNTIL TESTED.
TYPE A-2.—BURIED IN MOIST SAND FOR FIRST TWO DAYS, FORMS REMOVED, AND CYLINDERS EXPOSED TO ELEMENTS FOR REMAINDER OF TIME.
EACH VALUE IS THE AVERAGE OF 4 CYLINDERS.

Series A.H., No.	Age when Broken, days.	Type of Treatment.				Ratio of Compressive Strength of Type A-2 to Type A Cylinders, expressed as per cent.	Index of Decreasing Strength.
		A.		A-2.			
		Average Compressive Strength, lb. per sq. in.	Reliability, per cent.	Average Compressive Strength, lb. per sq. in.	Reliability, per cent.		
4	28	1233	2	884	6	71	
	61	1556	1	1065	5	68	
	120	1816	1	1237	5	68	3
5	33	852	3	757	7	89	
	120	1504	1	958	12	64	25
8	28	1436	3	1187	3	83	
	118	2191	4	1578	7	72	11
9	28	1266	1	873	2	69	
	121	1944	3	1283	6	67	2
12	28	1277	1	1038	3	81	
	121	1559	4	989	4	63	18
13	28	1127	1	1017	3	90	
	120	1517	5	1130	3	74	16
16	28	1123	4	1084	4	96	
	120	1689	7	1330	5	79	17
17	28	1043	7	918	7	88	
	119	1694	5	1229	5	72	16
18	28	1312	5	1318	5	100	
	120	1865	3	1508	6	81	19
Average	28	1185	3	1008	4	85	14
	120	1753	4	1249	5	71	

There are 224 cylindrical test specimens tabulated in Table I. These specimens were made with great care, using the following procedure: Sufficient concrete was removed from the road to fill one-fourth of the molds. These molds were filled at the same time and marked "A." A second sample was taken and a second set was made and marked "B." This was continued until four sets had been made. When four cylinders were to be exposed to the air, one cylinder was taken from each set and in that way the variation in the quality of the concrete exposed on the different days was reduced to a minimum.

The cylinders recorded in Table I were made and aged in the dry season and therefore the results should be very uniform.

The "reliability" term in Tables I and III indicates the percentage deviation of the mean from the actual compressive strength for the concrete under examination. This percentage serves as a basis for judging the consistency of the separate specimens that go to make up the mean or average value when comparing different average values.

It is computed as follows:[1]

$$\begin{aligned} a_1-m&=d_1\\ a_2-m&=d_2\\ a_3-m&=d_3\\ a_4-m&=d_4 \end{aligned} \qquad m=\frac{\Sigma a}{n}$$

Average deviation of a single specimen (a.d.) $= \dfrac{\Sigma d}{n}$

Deviation of the mean (A.D.) $= \dfrac{a.d.}{\sqrt{n}}$

The percentage deviation of the mean or average from the actual, or the "reliability" percentage $= \dfrac{100\text{ A.D.}}{m}$.

The average ratios of the compressive strength of the specimens exposed for different lengths of time to the compressive strength of the standard specimens is tabulated in Table I. These average ratios are shown graphically in Fig. 1.

A single series P.R. 72 is plotted in Fig. 2 to give the curve as shown.

In the figures, the abscissas represent the number of days exposed to the drying effects of the tropical air[2] after being buried in moist sand and before being broken, and the ordinates give the percentage of the compressive strength which each set of specimens (exposed for the indicated number of days) was found to have, assuming the compressive strength of the specimens cured according to standard conditions as 100 per cent.

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[1] H. M. Goodwin, "Elements of the Precision of Measurements and Graphical Methods," 1913, p. 16.

[2] During the dry season the temperature is very constant and the rainfall is negligible as shown by the following values: temperature, mean, 80° F.; maximum, 92° F.; minimum, 66° F.; 8 in. of evaporation a month; 0.2 in. of rainfall a month.

Thus, in Fig. 1, at the extreme left the strength of the specimens that have been buried in moist sand for the total length of time, 28 days, is represented as 100 per cent, and at the extreme right the percentage of this strength is represented for the specimens that have been exposed to the air 27 days after being buried for 1 day in moist sand. The curve shows that the compressive strength of the concrete exposed to the air after being buried in moist sand for one day is reduced to less than 60 per cent of the strength it would have attained if stored in moist sand for the total 28 days, that is, if treated under standard conditions, or, in other words, saturated with water.

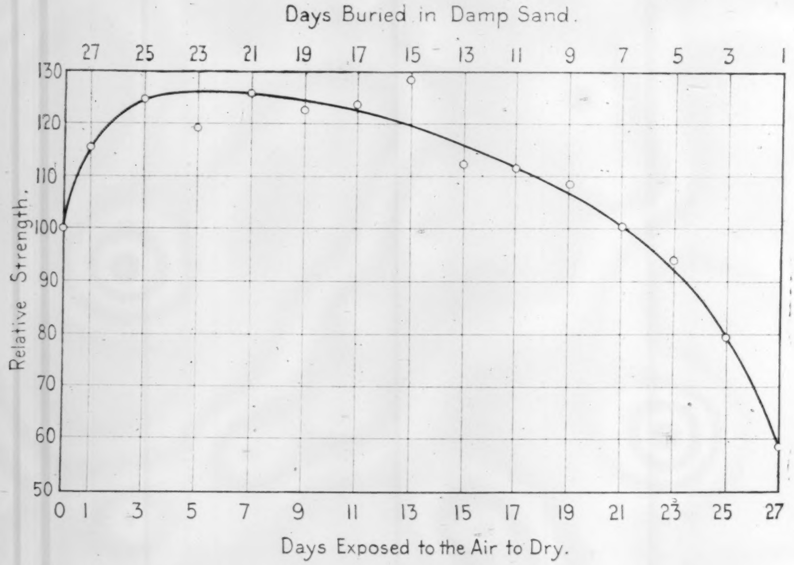

FIG. 1.—Average Ratios of Compressive Strength of Specimens Exposed for Different Lengths of Time to Strength of Standard Specimens.

The term "saturated with water" is used here because it has been found that by drying out the concrete the strength has been increased considerably. For example from the curve it can be seen that if the concrete is kept in a saturated condition for 27 days and dried for 1 day, it is 15 per cent stronger than it would have been if broken when saturated with water. If, however, it is allowed to dry for 3 days it would be about 25 per cent stronger. Longer drying seems to cause no appreciable increase and as it has been found that this period (3 days) coincides practically with the length of time required for the water to dry out from even the middle of the specimen, the concrete may be said to contain free water unless dried for at least 3 days.

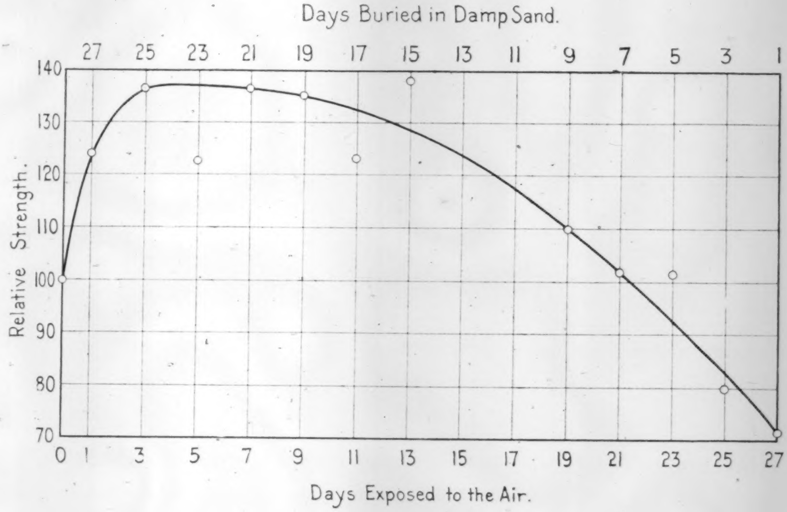

FIG. 2.—Plot of Test Results, Series P.R. 72.

In Fig. 2 the specimens dried for 3 days are 37 per cent stronger than specimens tested moist, and are more than 90 per cent stronger than specimens allowed to dry after being kept moist for but one day. The shape of the curves shown indicates that a chemical action takes place for about 20 days in the presence of excess water and that a considerable increase in strength results from this action. The decrease in strength when the specimen is wet is believed to be due to the physical action of lubrication, or perhaps to the noncompressibility of water.

It might be supposed by some that even though there were a very large variation in the compressive strength between the specimen buried for the total period previous to breaking, and the specimen buried for only 1 or 2 days when both specimens were broken in 28 days, the compressive strength would be more nearly equal if a longer period had elapsed.

This has been found to be a false supposition. Table III will show that in the sets broken in 4 months there is even a greater variance between types A and A-2 than in those broken in 28 days. While the specimens buried in moist sand for 2 days and broken in 28 days are 85 per cent as strong as those buried in moist sand for the total 28 days, the specimens buried in moist sand for 2 days and broken in 120 days are only 71 per cent as strong as those buried for the total 120 days. This shows an average increased difference of 14 per cent when the test specimens are considered.

These cylinders exposed to the air were also exposed to the wet season rains, which should have made the compressive strength after 4 months for the types A and A-2 nearly equal. It is believed that a much larger variation between the 28 and 120 day values as well as between the types A and A-2 specimens would result in the dry season when the rain fall is practically zero for about 4 months.

The Public Service Commission for the First District, State of New York, realized in 1914[1] that concrete saturated with water gave compressive strengths lower than dry concrete, for they specify:

"Specimens must be removed from the moist room to the laboratory two days before breaking in order that they may become dry. The strength of saturated specimens is considerably below that of dry ones."

A 2-day exposure to the air of a laboratory is rather a questionable and variable method of drying and from either curve it is easily seen that a small variation upon either side of the 2-day period is liable to cause a large variation in the compressive strength because at this time the specimen is losing its moisture rapidly and therefore its compressive strength is increasing rapidly. In other words, the curve is very steep at this time and therefore a small variation in the time of breaking causes a relatively large variation in the compressive strength.

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[1] *Engineering News*, Feb. 4, 1915, p. 207.

The optimum length of exposure to the air after being buried in moist sand has not been determined, for results have not been obtained to indicate whether specimens saturated with water or specimens dried for 4 days give the most uniform result. In view of the practical carrying out of a procedure in the ordinary laboratory, the author believes that more consistent results and, at least, strengths more consistent with those of the concrete in the structure will be obtained by specifying that concrete specimens shall be buried in moist sand from the time when poured until 4 days prior to the date of testing, at which time they shall be allowed to dry out by exposure to the air and protection against rain. They should be shipped to the laboratory during this period.

The length of time the specimen is allowed to remain in the laboratory, the temperature of the laboratory, its humidity, air motion and in general the conditions that would exert an effect on the drying out of the concrete, seem to have been entirely omitted from consideration by the different experimenters.

While experiments are under way that will determine more exactly the relative effects of these different factors, it is hoped that the curves given will serve to show the great effect that some of these variables must have.

Regarding the application of this curve to paving practice, it might be stated that the advantage gained by removing the water or moist clay from the surface of the pavement at least three days before the road is opened for traffic can easily be seen from either curve. The concrete, although perhaps a little green, will be aided greatly in withstanding the load of traffic for the first few days if the road is opened after having been allowed to dry out for three days.

The advantage of keeping concrete moist for as long a period of time as possible can be seen from either of these curves.

CONCLUSIONS.

1. The longer concrete remains moist the higher will be its compressive strength.

2. Concrete test specimens broken in 28 days which are

allowed to dry out for 27 days after being kept moist for 1 day have a compressive strength as small as 40 per cent of that of specimens kept moist for the total 28 days.

3. Concrete test specimens broken in 28 days which are allowed to dry out for 3 days after being kept moist for 25 days are often more than 40 per cent stronger than specimens kept moist for the total 28 days.

4. The greatest variation between specimens cured properly and improperly is often over 100 per cent.

5. Concrete specimens that are tested in the average laboratory should be either kept moist until the hour of breaking or they should be exposed to the drying effects of the air for 4 days, previous to breaking.

6. Any length of exposure between these two is likely to lead to errors of considerable magnitude due to small variations in the time factor.

7. The curing of concrete test specimens should always be described when any results on the compressive strengths of concrete are published. The length of time that specimens are drying in the laboratory prior to breaking should also be stated.

8. In concrete columns, beams, floors, and pavements the greatest compressive stress is always on the outside and usually on the top. It is therefore necessary to keep the outside layer moist for long periods of time in order that high compressive strength may be obtained, even though the member has considerable mass and therefore there is little danger of rapid loss of moisture taking place throughout the member.

The author wishes to express his appreciation for the helpful suggestions and criticisms which he has received from Mr. George C. Bunker, Physiologist, The Panama Canal.

PREVENTABLE DEFECTS IN REFRACTORY BRICKS.

BY C. E. NESBITT AND M. L. BELL.

SUMMARY.

In this paper attention is called to certain manufacturing defects which are found in commercial refractory bricks. These defective bricks pronouncedly shorten the life of the structure under service conditions.

The results of tests made on bricks before and after actual service are shown in the paper, illustrating the irregularities in quality.

Careful attention to the details of manufacture and visual inspection by the maker of the finished product will do much to raise the standard of commercial brick.

PREVENTABLE DEFECTS IN REFRACTORY BRICKS.

BY C. E. NESBITT AND M. L. BELL.

The importance of refractories in industry, particularly in the metallurgical industries, is unquestioned, as the output of these industries is largely dependent on the life of the furnaces, ovens, etc., and these in turn on the quality of the refractories used.

Under stress of great demand the refractory manufacturers during the past couple of years were called upon to produce rapidly large quantities of brick under conditions which seriously interfered with the quality of the product. This was immediately reflected in decreased life of furnaces and loss of tonnage in various industries.

This paper deals mainly with refractory brick used in the manufacture of iron and steel, but as nearly all the better known refractories are used in some one or more of the various processes, observations made here would apply to any industry where refractory bricks are used under similar conditions.

The life of the furnace, which may be expressed in terms of tons of material produced, number of heats, or weeks or years of service, is determined largely by the ability of the refractory used to resist numerous destructive agencies, such as temperature, slag, load, abrasion, etc. In blast furnaces the refractory comes in direct contact with the charge and is destroyed largely from abrasion, slagging, and softening. In open-hearth furnaces the silica refractory does not come in direct contact with the charge, but the roof, side walls and ports are destroyed chiefly by variations in temperature, slagging and abrasion due to particles of iron, lime, etc., carried by the moving gases. The slagging action due to material carried by gases is also a serious factor in the destruction of clay bricks used in soaking pits, reheating furnaces, air furnaces, etc. (Figs. 1 and 2).

The corrosive action of slag on refractories is recognized by all, but the fact that the strength of a brick is greatly reduced by penetration of slag is not generally known. In order to illustrate this point, four silica bricks were heated to 1350° C. (2462° F.) and a quantity of heating-furnace slag (approximate analysis: silica, 35 per cent; alumina, 6 per cent; ferrous oxide, 56 per cent) placed on the surface. At intervals the bricks were turned and the slag placed on other surfaces until it had penetrated all portions of the brick. These bricks, together with four others similarly heated but not treated with slag, were crushed on end separately while hot and the number of pounds necessary to fracture determined. The results obtained on the slag-free bricks averaged 1451 lb. per sq. in., while the slag-penetrated bricks averaged 775 lb. per sq. in., or a reduction in strength of 46 per cent. The appearance of the treated bricks when removed from the crushing machine was in no way different from that of the original bricks, except for discoloration, so that the decrease in strength can be accounted for only by

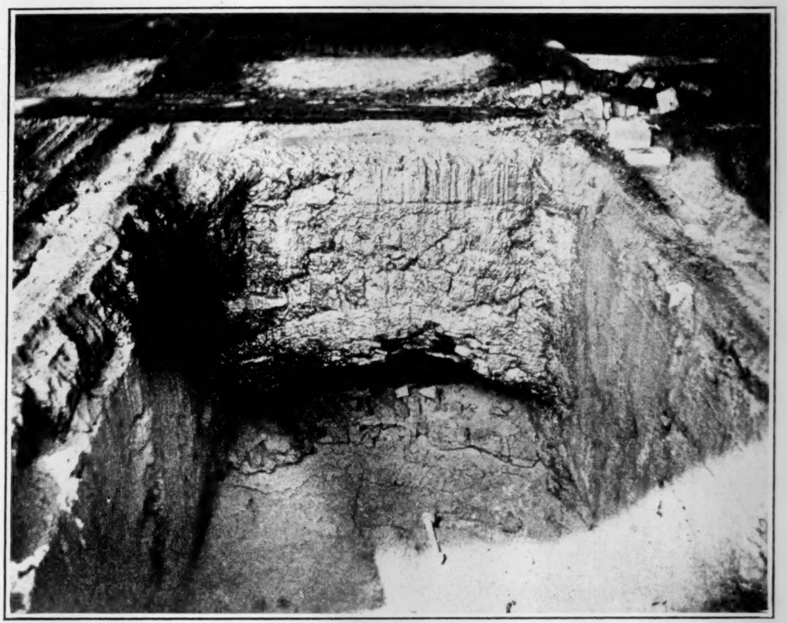

FIG. 1.—Interior of Soaking Pit Furnace showing Deterioration of Walls by Abrasion and Partial Fusion.

the action of the slag which had attacked and weakened the original bond.

In order to overcome this difficulty, a dense brick is advocated. It has been suggested that by proper sizing of the ground quartz, and by pressing instead of hand molding, a more dense brick can be secured, which is more resistant to slag penetration. Tests made for slag resistance on experimental power-pressed silica brick show approximately 25 per cent less penetration by heating-furnace slag than hand-molded brick.

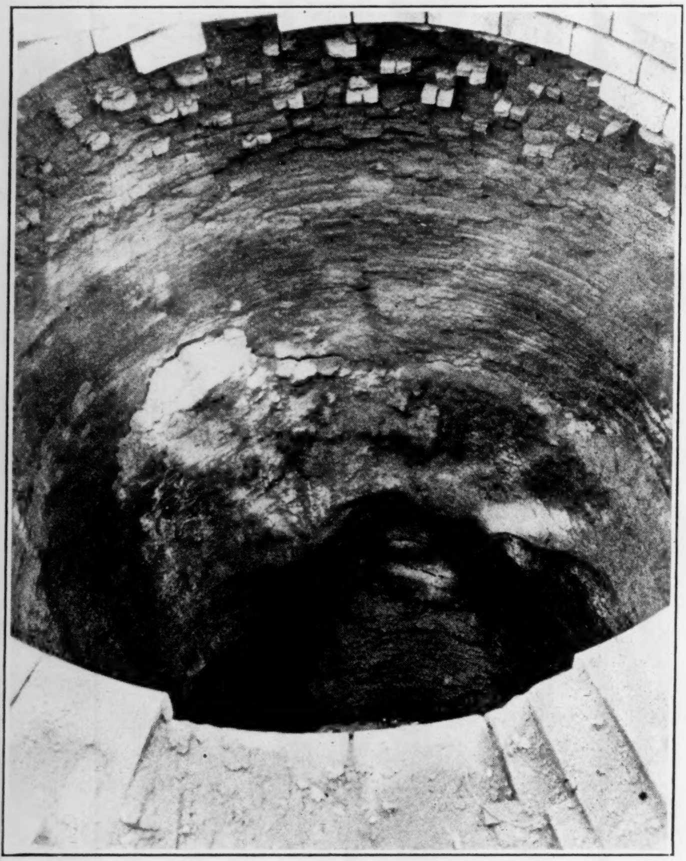

FIG. 2.—Wear at Top of Upper Inwall of Blast Furnace due principally to Impact and Abrasion. Note Large Pockets.

Silica brick show a marked falling off of from 50 to 60 per cent in crushing strength when heated to 1350° C. Hence, defects in molding, setting and burning become serious factors, as they lower the mechanical strength of a product which in itself becomes weaker by heat alone (Fig. 3).

In open-hearth furnace roofs, where the bricks must withstand considerable pressure due to the weight of the bricks in the long arch and expansion due to heat, a careful selection of bricks is necessary. A few defective bricks in a roof are liable to cause premature failure. Although actual crushing of the unit brick may not result, spalling or cracking will occur, so that a hole or pocket is formed and the adjoining bricks are thus more completely exposed to destructive agencies (Figs. 4 and 5).

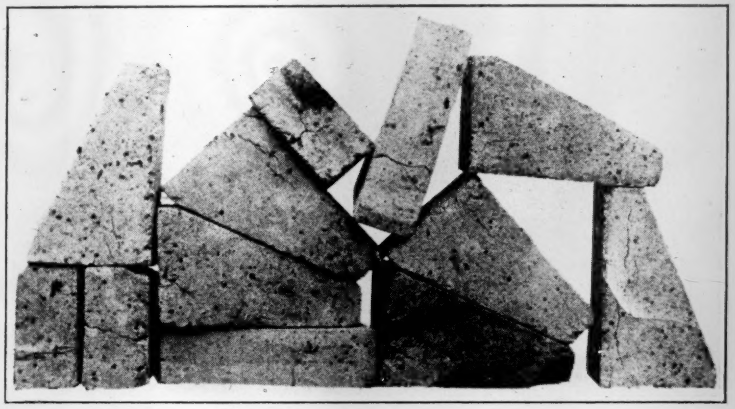

FIG. 3.—Defective Silica Shapes due to Imperfect Molding, Setting, and Fire Cracks.

Fully 80 per cent of the defective bricks received by the consumer can be detected by a careful visual examination. A group of 85 standard 9-in. silica bricks were subjected to visual inspection: 16 were judged to be of low strength because of visual defects; 18 were considered to be of medium strength, while the remainder were passed as being good. These bricks were then subjected to a hot crushing test. All bricks were crushed at 1350° C., with the result that the average strength for the 16 defective bricks was 677 lb. per sq. in., 861 lb. for the medium, and 991 lb. for the good bricks.

The presence of fire or kiln cracks in roof bricks, however minute, is a real menace, especially if the crack occurs near the center of the brick. Examples of failure of this nature can be found in nearly any open-hearth furnace roof of the present day. While this sort of defect is more common in silica brick, it may also occur in clay brick and cause the failure of arches (Fig. 6).

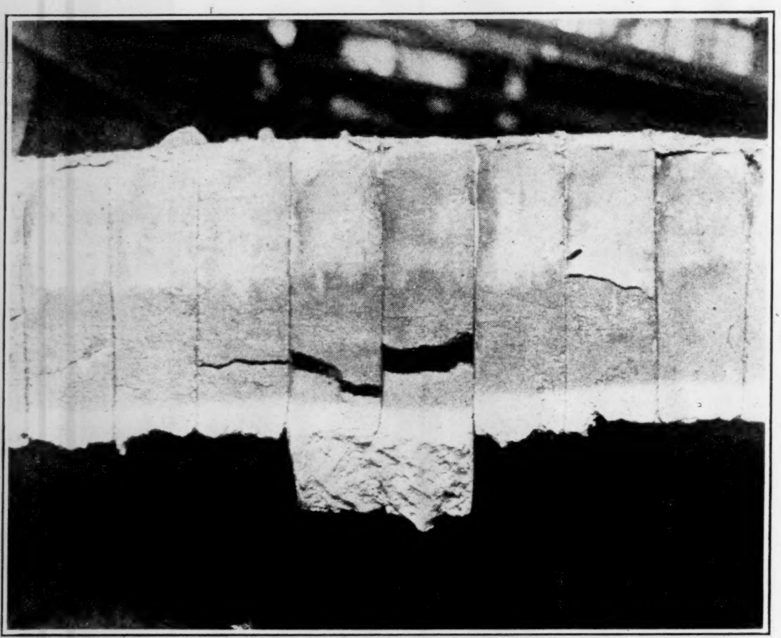

FIG. 4.—Unit Brick Failure due to Spalling in Open-hearth Roof. The Beginning of the Failure of the Roof.

It has been suggested that true specific gravity and porosity may be used to determine the quality of silica brick, but these tests only tell the degree of burning.[1] They are useful in determining the uniformity of burn of various shipments, but tell nothing regarding the actual mechanical strength of the bricks, particularly as regards the crushing strength at high temperatures. It is easy to prove that bricks which have the same true specific gravity do not have the same crushing strength or spalling value.

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[1] D. W. Ross, "Silica Refractories," *Journal*, Am. Ceramic Soc., July, 1918.

Some manufacturers of refractory brick do not seem to realize the importance of uniformity of product. In a car of silica brick recently received, it was found that the quality of the roof bricks and of the 9-in. straights were widely different. The roof bricks showed a true specific gravity of 2.39 with an average spalling loss of 17 per cent, but the individual results varied from 9 to 24 per cent. Their average hot crushing strength was 863 lb. per sq. in. The 9-in. bricks showed a true specific gravity of 2.53 with an average spalling loss of 29 per cent, the individual results varying from 26 to 30 per cent. The hot crushing strength was 1268 lb. per sq. in.

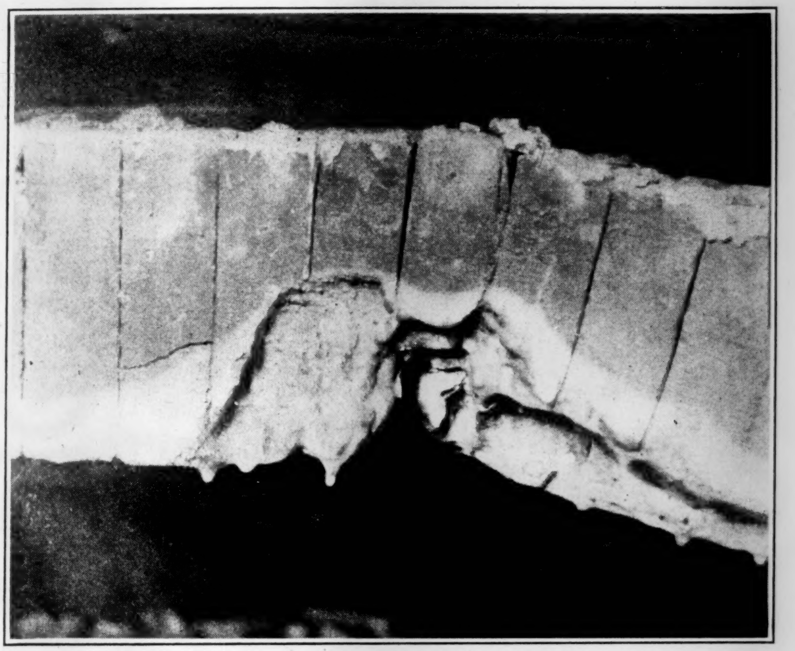

FIG. 5.—A More Advanced Stage of Unit Brick Failure as Illustrated in Fig. 4, caused by Spongy or Cracked Brick.

In the case of some roof bricks received during one shipment, it was found that the straights gave a hot crushing strength of 665 lb. per sq. in., while the No. 1 wedge bricks gave 1044 lb. per sq. in. It is recognized that these two sizes might not have been made at the same time, but they were presumably of the same quality. In another case it was necessary to use bricks from two different makers in an open-hearth furnace roof. The tests showed the spalling loss was 30 per cent for one make as against 10 per cent for the other, though the hot crushing strengths for the two makes were about equal. Such differences in bricks made in the same district, of the same raw material, and by approximately the same methods, should not exist (Fig. 7).

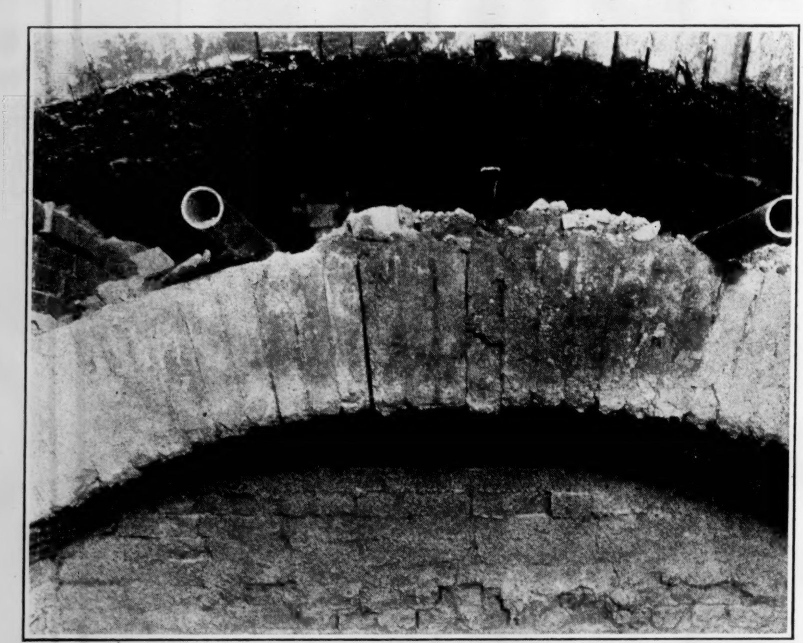

FIG. 6.—Spalling of Clay Brick in Soaking Pit Arch. Note Especially Unit Brick Failure.

Roofs of 90-ton open-hearth furnaces, working under normal conditions with producer gas, should last for at least 200 heats. Tests for resistance to spalling made on bricks taken from such a furnace after 261 heats have shown an average

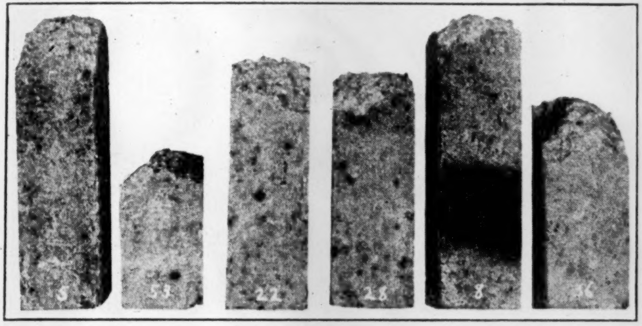

FIG. 7.—Variation in Resistance to Thermal Change as shown by Spalling Test of Silica Brick received in the same Car. Note Percentage Loss Marked on each Brick.

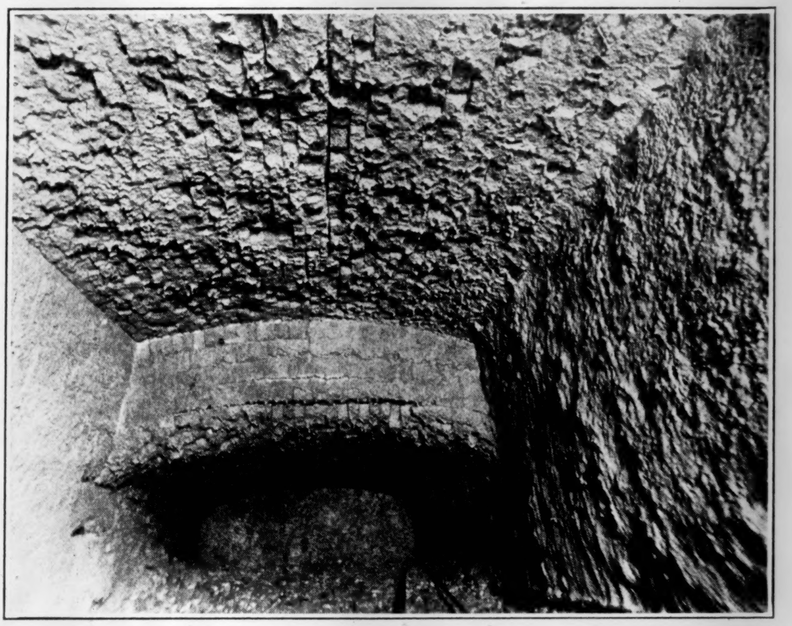

FIG. 8.—Variation in Clay Brick as shown by Spalling in Air Furnace Roof.

spalling loss of 20 per cent. Another roof which made 221 heats showed a loss of 23 per cent. In a similar roof used for only 80 heats, the average spalling loss was 47 per cent.

Two silica bricks were found side by side in an arch leading to the regenerator chamber of a furnace; one was badly spalled, apparently due to thermal changes or crushing, the other showed no trace of spalling or crushing. Both were of the same make and presumably made at approximately the same time. Subjected to a spalling test, the poorer of the two bricks showed a loss of 42 per cent against 27 per cent for the other brick.

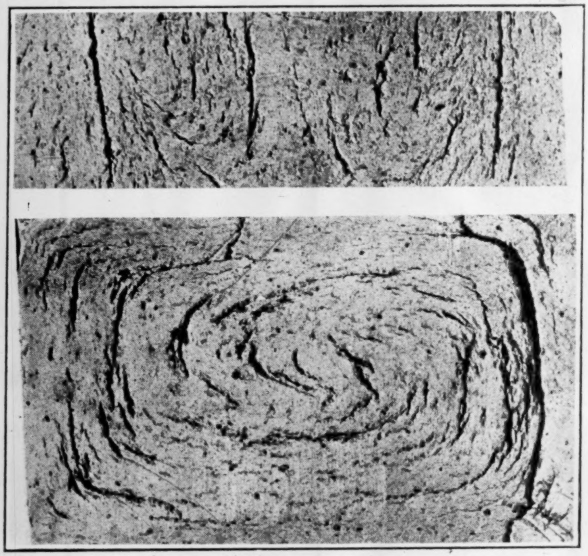

FIG. 9.—Laminations in Auger-Made Clay Brick.

Silica brick makers are not the only ones who fail to deliver a uniform product (Figs. 8 and 9). In shipments of clay checker bricks great variation in degree of burning was observed. Spalling tests were made on those of average burn which showed a loss of 14 per cent, while the hard blocks showed 60 per cent loss.

Among users of refractories there is a growing demand for a product of uniform quality, especially with regard to defects which are preventable if the material is properly handled.

The user of bricks pays a fair price for the bricks he purchases and is entitled to a fair return for his money. It is to be regretted that more thorough inspection is not practiced by the brick maker before shipment. A certain amount of visual inspection is practiced, and users of bricks from several makers soon recognize that certain firms invariably deliver goods which on the whole are uniform in quality. For bricks delivered which are warped, twisted, fire-cracked, variable in degree of burn or texture, spongy, laminated, badly molded and slicked, or of impure material, the maker is at fault.

Some manufacturers of brick do not seem to realize the importance of uniformity of product. The buying of bricks on specifications has not been universally followed, and it is partly through the ignorance of the consumer in not understanding what he wants and why he should ask for certain qualities, that the quality of refractories is not maintained at a higher level. In using refractories the consumer assumes that the bricks he purchases will be of the same average quality as those he has formerly received. That this assumption is not always correct is unfortunate.

A recent shipment of 100,000 special roof and arch bricks was inspected by a consumer, and it was found that over 10 per cent were defective. The purchaser had paid the market price for these bricks and had a right to expect uniformity in quality. It is not the desire of any consumer to force specifications, yet he may have to do so in self-defense. The consumer has no right to tell the manufacturer how to make the bricks, but he is justified in demanding that certain requirements consistent with commercial manufacture be met.

The material from which bricks are made largely determines the heat-resisting qualities, but it is the method and care in manufacture which determines the uniformity and reliability of the finished product. A careful inspection through all the steps of manufacture will accomplish much towards the betterment of quality by eliminating irregularities which reflect in the finished product.

DISCUSSION.

Mr. Unger. MR. J. S. UNGER (*presented in written form*).—The authors of the paper have shown that many refractory bricks are cracked, broken, warped or otherwise physically defective and lack uniformity. This is a subject in which every brick consumer is interested.

Experimental data obtained from a study of bricks, whether it be of the raw material, the manner of manufacture, or the finished bricks, has little value until it has been applied commercially. If an attempt were made at a given plant to manufacture bricks by those methods which have experimentally shown the best results, the radical changes involved might mean the discarding of almost all of the plant equipment, causing serious financial loss. It necessarily follows that pronounced changes in the method of manufacture of bricks must be made slowly.

Refractory bricks are subjected to many different classes of service. The consumer will gage their quality from the life he obtains in his particular service and will insist on securing bricks which give the longest service. Such bricks may not serve as well for another purpose. It is this difference in service which renders it very hard to specify a particular kind of test to cover all needs, as each user will want a test covering his particular requirements.

If a user were to suggest methods for making brick, some makers might consider it presumptuous, and insist on the user being responsible for the quality if his methods were followed. Such shifting of the responsibility would lead to controversy. As a consequence, each manufacturer should make a study of the user's needs and produce a brick best fitted for his particular purpose. The user cannot hope to get the best results for his various needs from stock brick, which were made to be used in general service. For some purposes stock bricks may be of better quality than necessary, while for others they may not be good enough. It appears that the best bricks can only be made on a specific order for a specific service.

Mr. Unger

A shape brick and a straight 9-in. brick may be laid side by side in a furnace and subjected to the same destructive influences. It is a common practice to make shape bricks of slightly different proportions of raw material, to grind to a different degree of fineness and to use a different amount of water in the pug. These differences influence the durability of the brick, and this practice should not be followed.

Bricks are a heterogeneous mass from their very method of production. It is well known that bricks of the same brand differ in properties, but it is not so well known that the different ends of the same brick may show differences in the ratio 1 to 3 in their resistance to abrasion, slagging and crushing. This brings out very forcibly the lack of uniformity which must be corrected to give a uniform life.

Proper proportioning of the several raw materials is not always done, nor are injurious or foreign materials rejected, such as, sand, stone, shale, sulfur balls or high iron-bearing materials. Wet pan grinding cannot produce the proper proportion of the fine and coarse material, nor the best water content. Molding by hand, extrusion in an auger machine, and either method followed by a pressing operation, do not furnish the best quality for all bricks. Other things being equal, a coarse-ground pug will show a lower spalling loss and is less susceptible to rapid thermal changes than a fine grind, but the coarse grind shows a greater slag penetration and lower crushing strength. It is obvious that the maker is prevented from going to the extreme in any one direction in order to improve a certain property, without affecting some other property.

A few tests at intervals are not sufficient to control the manufacture of bricks. Uniformity can only be obtained when such yard tests and inspection are made daily or hourly on the ground material, the green brick and the finished brick as will control the fineness, proportionate sizing, moisture, imperfect molding, drying and degree of burning.

Burning a silica brick until the quartz is completely changed to a more stable form might produce a very excellent brick for some purposes, but if such burning increases the cost to a prohibitive degree without giving a corresponding additional life, it is not a commercial proposition.

If a brand of bricks used in a particular service gives a

Mr. Unger. certain average life and a new lot of the same brand is used in similar service in the same furnace at another time and gives but one-fourth of the life, either the bricks or the service or both are different. If it can be shown that the service is not at fault, would it not be better to purchase bricks on a guaranteed life, rather than on some test, in much the same manner as many articles are sold, such as a guaranteed mileage for an automobile tire?

The ordinary "kiln-to-car" inspection practiced at many yards is not thorough, as sufficient time is not allowed to properly inspect and reject defective bricks, while no time is available to make any extensive tests for quality. When this condition is remedied, all poor bricks will be culled out, and the maker, when confronted with the number of defective bricks he produces, will of necessity apply remedies in the manufacture that will prevent such bricks from being made and shipped.

Mr. Howe. MR. RAYMOND M. HOWE (*presented in written form*).—The general trend of this paper would lead one unacquainted with the refractory industry to believe that the manufacturers of fire brick had marketed an extremely poor product during the war, and that they are continuing to do so. Careful inquiry on the writer's part has convinced him that, generally speaking, such a conclusion is not justified.

Particulars are available which show how the refractoriness of several brands in 1918 compared with that observed in 1915; these particulars follow:

Brick No.	Fusion Point, 1915 Cone.	Fusion Point, 1918 Cone.	Brick No.	Fusion Point, 1915 Cone.	Fusion Point, 1918 Cone.
1	31¼	32	14	30	30
2	27½	27	15	30¾	32
3	29¼	29	16	31¼	31
4	31	31	17	28¾	29
5	32	32–33	18	31	32
6	29	29	19	29	29
7	31¾	31	20	30	31
8	32	32–33	21	32	29
9	31¾	31–32	22	32	32
10	31¼	31–32	23	31¼	32
11	31	31–32	24	32¼	32–33
12	31¼	31–32	25	29¼	29
13	32½	33	26	31¾	32

These data show that in nine cases out of 26 the product in 1918 was of higher refractoriness than in 1915, in six cases the product was more refractory in 1915 than in 1918, and in eleven cases the difference was too small to be determined. This condition is due very largely to the fact that the refractoriness of fire clay is not changed in the process of manufacture, since water is the only other material which is added and all other steps are purely mechanical. It is true that occasional sulfur balls or slate may enter the mix, but with sorting at the mine and pans the opportunity for such contamination is slight. Were the workmen as careless as might be inferred from the paper under discussion, the results would show up very clearly in the tests which have been cited. **Mr. Howe.**

The only other deterioration in the quality of fire brick concerns workmanship, and those bricks which are poorly made are easily detected by the eye and should be discarded.

The tests which are given in the paper are ones which chiefly concern the structure of the finished ware. Were like tests applied to concrete and other products similar in structure to fire brick, the same variations would be noted.

It may be of interest to know that a large engineering corporation was recently concerned about the quality of refractories. A questionnaire was circulated by that organization and the results turned over to the writer. The consensus of opinion expressed in the answers to this questionnaire was that if the same progress had been made in the selection and use of fire brick and in furnace construction as had been made by the manufacturers, fewer fire brick complaints would be heard. Variable operating temperatures, poor furnace design, the use of corrosive mixtures, over-insulation, the use of inferior mortar, and similar poor practices often lead to failures which are blamed upon the manufacturer, although he is not responsible for the treatment of the product after it leaves his plant. When bricks are cut away, or spall away after becoming impregnated with slag, or are eroded by the passage of gases or solids, it is difficult to conceive of a fire brick that would resist such influences and retain its refractoriness.

MR. W. P. BLAIR.—I should like to ask Mr. Nesbitt whether the variations in the gases and in the influences that are destruct- **Mr. Blair.**

Mr. Blair. ive of any particular brick in the soaking pit cover illustrated on the screen just now are not just as great as the variations in the bricks themselves, put there to resist those influences. It seems to me, without knowing what those influences are, that it is utterly impossible to meet them by any fire brick manufactured.

Mr. Stone. MR. G. C. STONE.—Our thanks are due to Messrs. Nesbitt and Bell for their excellent paper, drawing attention to the common preventable defects in refractory brick.

The company that I represent has nine smelting works located at widely separated points and has bought refractories from fifty or sixty makers located mainly in New Jersey, Maryland, Western Pennsylvania, Missouri and Colorado. In all cases we find the difficulties illustrated by Messrs. Nesbitt and Bell. The proportions of defective brick vary greatly in different shipments, not only in those of different makers but also in shipments from the same makers. We have received shipments with a very small proportion of imperfect brick, sometimes less than 1 per cent but usually with a larger proportion; in one case nearly 80 per cent were defective.

In addition to the brick we buy we make a considerable number, as we have been unable to purchase satisfactory brick for certain types of furnaces. While we purchased these brick we were unable to get a longer life for a lining than about a year and a half, but brick of our own make are giving a life of about ten years. This, it will readily be seen, greatly increases the productive capacity of our plant.

I have visited many plants making refractories, and have reports on many others, a large number of which show there is considerable carelessness in manufacture which leads to variation in the quality of the product. In practically all cases there is inadequate inspection, which leads to the shipment of defective material. I believe that the manufacturers make a mistake in not inspecting their brick more carefully, as inspection should be cheaper than paying claims for defective material. One thing that has probably delayed this is that most consumers do not know much about brick, and a lot that is rejected by one customer can usually be sold to another with slight loss to the producer. Purchasers frequently do not reject poor material on account of the delay that would be involved in replacing it. If the consumers would regularly make claims for compensation for defective refractories, the manufacturers would be more careful in inspecting their shipments, and metallurgical practice would be much improved. **Mr. Stone.**

MR. C. E. NESBITT.—In answer to Mr. Blair, I would say that the bricks in the soaking pit cover illustrated on the screen were first grade refractory clay brick, and they showed a wide variation. There are several illustrations in the paper, especially Figs. 4 and 5, that show variations in bricks nearly as great as those in the soaking pit cover illustrated. **Mr. Nesbitt.**

MR. J. D. RAMSAY (*by letter*).—It is evident to anyone familiar with the manufacture and use of refractory brick that the authors of this paper have made some very broad and sweeping statements without furnishing adequate proof. They have in numerous specific instances pointed out refractory brick failures, both silica and fire-clay, and have invariably placed the entire blame at the "doors" of the manufacturers, regardless of the cause. Where failures have been referred to, they have stated uncompromisingly that the brick were of inferior quality, not properly manufactured and not thoroughly inspected prior to shipment. In this discussion they have absolutely ignored the many other factors which may be responsible for the failure of the brick and have displayed an unwillingness to admit the irregularities in operating conditions under which refractory brick are used. **Mr. Ramsay.**

It is a fact, well known to all men of experience, that furnaces identical in design and operated by the same men show different results. Since this is true it is evident that furnaces of different designs, making a variety of products and operated under widely different conditions, depending on the variable human element for their operation and control, should and do show a greater variation in the results obtained; yet the authors make the assertion that observations referred to by them "will apply to any industry where refractory brick are used under similar conditions." They have failed to prove that conditions in other industries are similar to those prevailing in steel mills, much less that conditions in all steel mills are identical. They further state that the "life of the furnace is determined largely by the ability of the refractory used to resist destructive agencies such

Mr. Ramsay. as temperature, slag, load and abrasion," yet they disregard the fact that an operator may literally ruin his furnace in a few heats by careless and erratic operation, or that a mechanic may improperly design and construct the furnace in a way which will materially shorten the life of the lining.

In Fig. 1 of this paper a soaking pit is illustrated, pointing out the deterioration of the walls due to abrasion and partial fusion. The authors do not state how long these brick linings have been in service at the time the photograph was taken, nor do they admit that any material, if exposed to abrasion for a sufficient length of time, will wear away, or will partially fuse when exposed to excessive temperature if sufficiently fluxed. The grooved sides shown in the cut could very easily have been formed by cutting tongues of flame which were caused to play along the side walls by some "freak" of draft conditions. Under such exposure a very superior brick would show deterioration before other portions of the lining, which were not exposed to similar flame action.

The authors also show examples of "unit failures" by spalling, due to irregularities of the brick used. They have failed to prove that the breaking of these brick was not caused by improper fire masonry, inferior quality of mortar, or improper care of the brick before they were put in service. It is just as logical to assert that this failure was due to improper care of the material, defective masonry or poor mortar as to state that "defective brick produced the poor results." The brick may have been exposed to rain, frost or freezing before being laid in the arch and its resistance thereby greatly impaired. When the arch was laid up, the broken brick may not have been seated snugly against the adjoining brick and the weight of the arch may have caused the break; or again, the mortar may have been of inferior quality and fused, coating the brick with a vitrified glaze sufficient to cause spalling. They try to prove by these exceptional examples that "manufacturers of refractory brick do not seem to realize the importance of uniformity of product."

We note that the authors recommend, as a remedy for their grievances, specifications for the selection of the refractory brick required. We ask, by what standards will these specifications be drawn, when conditions of service in furnaces are widely

Mr. Ramsay different? It is admitted that brick with physical defects, clearly shown by "visual inspection," should be withheld from shipments, but they have offered no proof that such selections would obviate all fire-brick troubles. They seem to forget that hidden imperfections may be discovered in any manufactured commodity, providing you seek long enough for them, even in high-priced articles where the selling price warrants the cost of extra "visual inspection."

They fail to admit that only a few consumers are inclined to furnish the producer with details of the conditions under which the brick are to be used and yet they say "that it is not the desire of any consumer to force specifications, yet he may have to do so in self-defense." We submit that the most valuable specification which the consumer can supply is a complete statement of the working conditions of the furnace in which the brick are to be used. This will assist the manufacturer in producing an article suited to meet such conditions.

In the opinion of the writer, promiscuous and unfounded statements have been made throughout this paper which tend to cast adverse reflections on the manufacturers of refractory brick as a whole. Instead of relying on friendly cooperation with the manufacturers as a remedy for their particular grievance, they have resorted to unwarranted criticism directed against manufacturers of refractory material in general, with the idea of bettering conditions.

In conclusion we submit the following criticisms of this paper:

1. The statements are entirely too general, considering that the experiments were made with only a few brands of brick and in the steel industry alone.
2. The writers of the paper admit "that certain firms invariably deliver goods, which, on the whole, are uniform in quality." Therefore, their complaint refers to some producers and should be filed with these specific firms instead of attacking the whole industry.
3. They attempt to show that 80 per cent of fire-brick failures are traceable to improper "visual inspection," but they have failed to prove it by statistics, except by taking a specific brand of brick and subjecting it to a laboratory test.

Mr. Ramsay. 4. Their experiments deal entirely with the conditions prevailing in the steel industry, which are not identical with those obtaining elsewhere.

5. They have failed to suggest a set of specifications which would be of practical value to the producer or the consumer.

Mr. Nesbitt. MR. C. E. NESBITT (*Author's closure by letter*).—In reply to Mr. J. D. Ramsay's discussion of this paper, I think it advisable to take up his various points in their order. It is not the intention of the authors to publish anything harmful to the refractory brick industry, but merely to point out that preventable defects exist which cause wide variations in the present-day product.

We deny that we invariably place the entire blame on the manufacturer regardless of the cause, but in support of our title the evidence we have selected shows that the manufacturer is to blame in many cases.

After studying the third paragraph on page 623 and the first paragraph on page 626 showing wide variations in new unused bricks direct from the manufacturer, and from a study of the variation of bricks in service illustrated in Figs. 2, 4, 5, 6 and 8, one logically draws the conclusions that the bricks might be improved either in manufacture or by more thorough inspection.

Mr. Ramsay's argument about "similar conditions" is wrong. The word "similar" has a broad meaning and must not be confused with identical. In other industries I have seen bricks which have failed in the same way as in the steel industry under similar conditions. We do not claim the complete elimination of the human element. Our statement reads "the life of the furnace is determined *largely* by the ability of the refractory, etc."

Mr. Ramsay's suggestion that the deterioration illustrated in Fig. 1 could have been caused by some freak condition of the draft, is not correct. Freak draft conditions seldom affect the entire pit and the other pits around it.

Mr. Ramsay states that unit brick failure may just as logically be due to poor workmanship in laying the brick, poor mortar, or the weather exposure of the brick. If such be the case, why should one or two bricks fail surrounded by apparently good brick? I should like to call his attention to the second

Mr. Nesbitt. paragraph on page 628 in which the unit brick which failed had a spalling loss of 42 per cent and the brick beside it only 27 per cent.

We do not want specifications unless forced to use them in self-defense, and then the demands must be borne out in actual service. We do not claim that this would obviate all our fire-brick troubles. As we have already stated in the paper, many consumers, through a lack of study of the use of refractory brick, are unable to give the manufacturer the information he wants and many manufacturers are inclined to let "well enough" alone. Again, I wish to point out that the correction of the preventable defects which we have mentioned will do much to raise the standard of bricks.

Referring now to the conclusions at the end of this discussion, I shall reply categorically as follows:

1. We cannot agree with Mr. Ramsay, as our studies have covered the refractory brick received at our various plants or about 100 million bricks, which is about 20 days output of the annual production of refractory brick throughout the United States.
2. No producer furnishes brick sufficiently free from commercial defects or of uniform quality.
3. We stand by the statement as given in our paper.
4. We have purposely dealt entirely with the steel industry, but we have observed similar conditions in other industries and similar brick failures.
5. The paper was not written for the purpose of suggesting specifications. Its subject, we believe, is perfectly clear and we have adhered to it.

PAINT, A PLASTIC MATERIAL AND NOT A VISCOUS LIQUID; THE MEASUREMENT OF ITS MOBILITY AND YIELD VALUE.

BY E. C. BINGHAM AND HENRY GREEN.

SUMMARY.

In this paper the differences are pointed out between viscous and plastic substances. A viscous liquid will start to flow no matter how small a pressure is applied. With plastic materials no flow takes place until after the pressure has exceeded a certain definite value, to which the term "yield value" is given. Plastic substances are therefore more correctly classified as solids.

Paint is shown to be a plastic material and not a viscous liquid. This classifies paint as a solid, and we refer to it as being "rigid" or "mobile," rather than viscous or fluid.

The plastometer, an instrument designed to determine the mobility and yield value of plastic substances, is described. The method of measuring mobility and yield value is given. Formulas for calculating these properties from the laboratory measurements are worked out.

Experimental data are presented and discussed. The practicability of the apparatus is shown. It is also applicable to various research problems found in paint work.

PAINT, A PLASTIC MATERIAL AND NOT A VISCOUS LIQUID; THE MEASUREMENT OF ITS MOBILITY AND YIELD VALUE.[1]

By E. C. Bingham and Henry Green.

Introduction.

The determination of the absolute viscosity of paints in c. g. s. units has always been a problem of considerable interest to the paint chemist, but one which unfortunately presents difficulties that are not, as a rule, so generally understood nor so easy to overcome as might be desired.

The main difficulty has invariably arisen through a misconception of the very nature of paint itself. Is paint a viscous material? If so, we should be able to determine its viscosity with but little trouble after the well-known method of Poiseuille, by obtaining the rate of flow under a given pressure through a capillary of known dimensions. Thus:

$$\eta = K'\frac{P}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)^2$$

where K' is a constant derived from the dimensions of the capillary and P is the pressure which causes a volume of flow per second, V.

When this method is employed, the coefficient of viscosity is apparently not constant but varies with the pressure. Bingham[3] has shown, by using variable pressures, that for true liquids if P be plotted against V (suitable correction being made for kinetic energy), the relationship is perfectly linear and the curve passes through the origin, as in Fig. 1. However, when a plastic substance, such as a suspension of clay in water was used, the relationship was expressed by Fig. 2. We can see that a viscous liquid will start to flow no matter how small a pressure is applied. With plastic materials no flow takes place until after the pressure has exceeded a certain definite value (*f*, Fig. 2). This is exactly analogous to the case of many metals, where *f* is the yield value, beyond which flow follows the same law as it does for true liquids. Plastic substances are more correctly classified, then, as solids.

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[1] A contribution from the Research Laboratories of the New Jersey Zinc Co.

[2] For complete formula see Bingham, *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 375 (1918). In our instrument the kinetic energy correction was negligible.

[3] E. C. Bingham, "An Investigation of the Laws of Plastic Flow," *Scientific Paper No. 278*, U. S. Bureau of Standards.

Returning to the case of paints, if we use the variable pressure method[1] and plot *P* against *V*, the form of the graph obtained is that given in Fig. 2 and not Fig. 1. Hence, *paints are not viscous liquids but highly mobile plastic solids*, and it is therefore obvious that their viscosity cannot be determined from Poiseuille's equation as it stands.

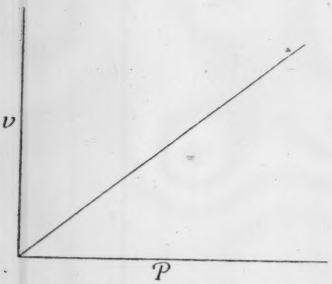

FIG. 1.—True Liquids.

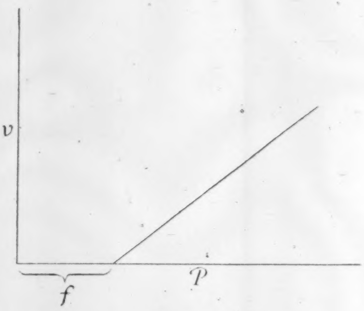

FIG. 2.—Plastic Substances.

If paints are to be classified as solids, it is no longer correct to refer to their "viscosity" or "fluidity," for these terms are applicable only to true liquids. We will then refer to paints as being "rigid" or "mobile." Table I shows the relationship of the terms used in this paper.

TABLE I.—RELATIONSHIP OF CERTAIN TERMS.

SOLIDS (including plastic materials)		LIQUIDS.
Rigidity (R)	Comparable with	Viscosity (η)
Mobility (μ)	Comparable with	Fluidity (ϕ)
$\mu = \frac{1}{R}$		$\phi = \frac{1}{\eta}$
Yield Value (f) is finite.		Yield Value is zero.

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[1] E. C. Bingham, "The Variable-Pressure Method for the Measurement of Viscosity," *Proceedings*, Am. Soc. Test. Mats. Vol. XVIII, Part II, p. 373 (1918).

It follows from the linear character of the curve passing through the origin in Fig. 1, that the flow is directly proportional to the pressure, in other words P/V is a constant. This slope for different fluids, measured in the same instrument, is proportional to the viscosity. Such is not the case with a plastic material as can be seen from Fig. 2. However, for a plastic material the slope is accurately defined by $V/P\text{-}f$, where f is the intercept of the curve on the pressure axis. And now we have

$$R = K' \frac{P\text{-}f}{V} \qquad (2)$$

$$\text{or} \quad \mu = K \frac{V}{P\text{-}f} \qquad (3)$$

So far, we have said little concerning the factor f, and nothing at all as to its real significance. In his paper on the Laws of Plastic Flow,[1] Bingham showed that for clay suspended in water there was a positive yield value[2] but it had not been determined that such a factor as f existed for paints. We are now in a position to state that f is not only a measurement of just as important a property of paint as the mobility, but it is far more interesting; its very unfamiliarity being sufficient to stimulate further investigation in a heretofore unsuspected direction, which eventually must add considerably to our knowledge of the mechanical forces that play so important a part in controlling the character and nature of paint.

The yield value is evidently the force required to start the flow. Even a very viscous substance such as pitch flows under a very slight pressure like water or any fluid. A plastic material like paint has the property of retaining its position or, less elegantly, of "staying put" after the pressure required to put it into the desired position has been removed. Paint thus behaves like clay in the hands of the ceramist in that it will maintain a vertical surface provided the weight is not too great to exceed the yield value.

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[1] *Loc. cit.*

[2] Bingham in his original paper used the term "friction." Since in solids the flow is dependent upon the yield point, it seems desirable to use the term "yield value" as synonymous with the friction.

We can have two paints with identically the same mobility, but one will flow from a spatula in a continuous stream, while the other is just able to drop off. Formerly we would have said that there was a difference in "viscosity," but now we know that the difference is in the yield value, the former having the lower yield value of the two.

A well-known example is that of a paint thinning down upon aging. We have examined a number of these and have not been able to measure any appreciable change in their mobility; there was, however, a decided falling off of the yield value. This new factor, the yield value, is evidently closely connected with the ease with which a paint flows when under small pressures—its own weight for instance. Obviously, the densities must be considered if comparisons are drawn, say, between a lead and a zinc paint, for the former with its density of 3 will require a much higher yield value than the zinc paint with its density of 2, if it is to retain its position when placed on a vertical surface. The mobility, evidently, depends on the viscosity of the vehicle, the amount of pigment, and, no doubt, the physical and chemical properties of the pigment present.

We are now in a position to predict the nature of a paint, knowing its mobility and yield value.

μ high and f low	thin, "runny" paint.
μ low and f low	thick, "runny" paint. Will probably drag under the brush ("stringy" paste).
μ high and f high	Will not run easily, nor will it offer much resistance to the brush.
μ low and f high	Will have good body, covering power and easily "stay put."

Reviewing our ideas thus far presented:

1. A definite appreciable force must be applied to a paint before it commences to flow. This force we have called the yield value.

2. The fact that paints have a yield value shows that they are not true liquids; they are plastic solids.

3. The yield value and mobility completely define the plasticity of a paint. It is these measurements we desire rather than the so-called "viscosity."

EXPERIMENTAL

APPARATUS

The Plan.—As we wish, in a sense, to measure the "plasticity" of a paint the apparatus for making the measurements has been called a "plastometer." Before giving a detailed description, a brief idea of the plan followed will be helpful.

Paint is to be forced through a capillary. Air under compression gives the necessary pressure. There must be a means of varying this pressure and also of measuring it. The volume of paint forced through per second, under any given pressure, must be obtained. Pressure is plotted against volume. The intercept on the pressure axis gives the yield value. The mobility can then be determined by Eq. 3.

The Plastometer.—This consists essentially of four parts: A pressure tank, *A* (see diagrammatic sketch, Fig. 3), a pressure regulator and stabilizer, *B*, a manometer, *C*, and a container for holding the paint, *D*.

The Container.—This is constructed of brass and holds about 15 cc. of paint. It is made in three sections; a top, a middle part and the lowest section which holds the capillary, *E*. A weighing tube, *F*, for receiving the paint as it comes through the capillary, is held in place by a rubber ring, *G*. The weighing tube is kept at atmospheric pressure through the side tube, *H*. The container is kept at constant temperature in a water bath, *I*. This is equipped with a stirrer, an inlet and outlet for water and a gas burner for raising the temperature as desired. Automatic control of the temperature is not necessary but is convenient. A three-way stop-cock is introduced at *J*.

Four screws, two at the top and two at the bottom, hold the container together. It is easily taken apart and cleaned.

The capillary is soldered in by means of a low fusion alloy composed of two parts bismuth, two parts lead and one part tin. It is necessary to have a number of capillaries of different "speeds" permanently mounted in this manner.

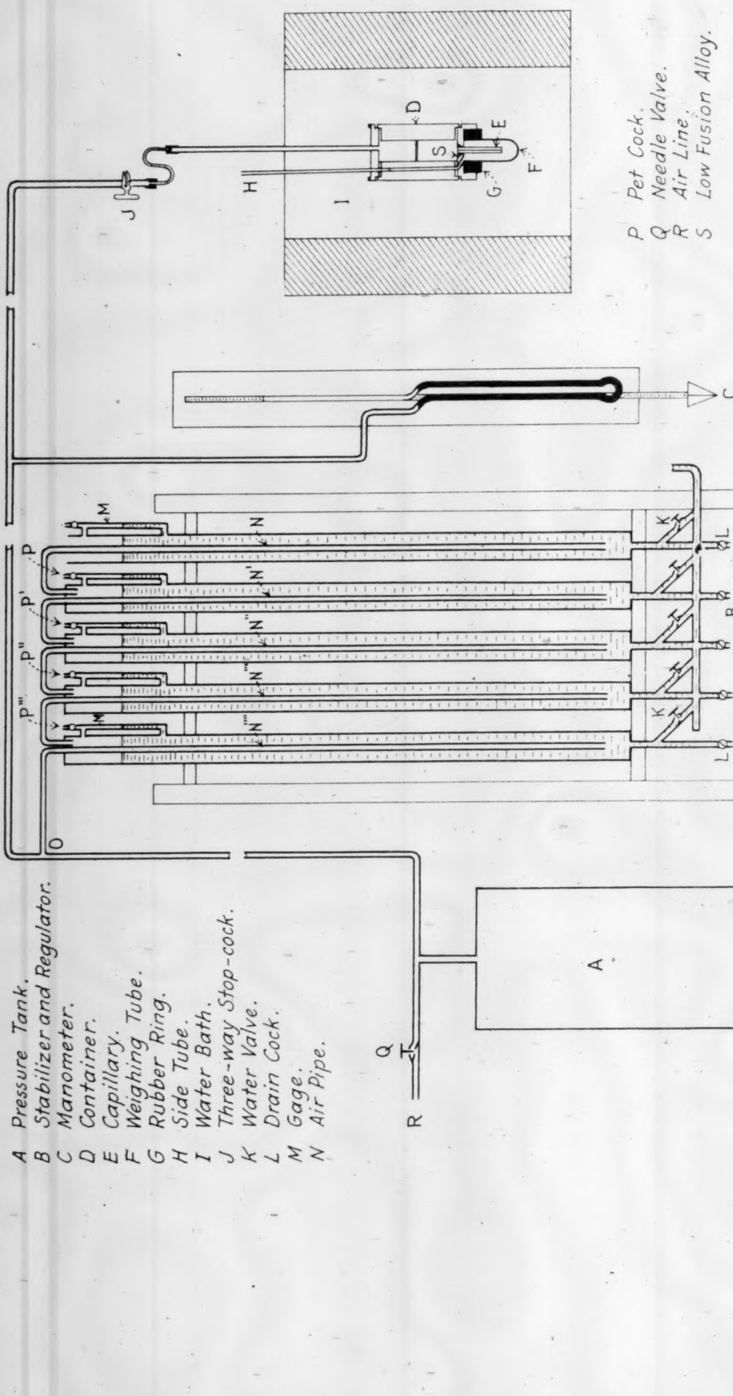
A Pressure Tank.
B Stabilizer and Regulator.
C Manometer.
D Container.
E Capillary.
F Weighing Tube.
G Rubber Ring.
H Side Tube.
I Water Bath.
J Three-way Stop-cock.
K Water Valve.
L Drain Cock.
M Gage.
N Air Pipe.
P Pet Cock.
Q Needle Valve.
R Air Line.
S Low Fusion Alloy.
A
B
C
D
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FIG. 3.—Diagrammatic Drawing of Plastometer.

The Manometer.—This is constructed in such a way that only one scale is necessary, making it very easy to read, and no special attention or adjustment is required. The photograph of the plastometer, Fig. 4, and Fig. 3, *C*, explain this part of the instrument completely.

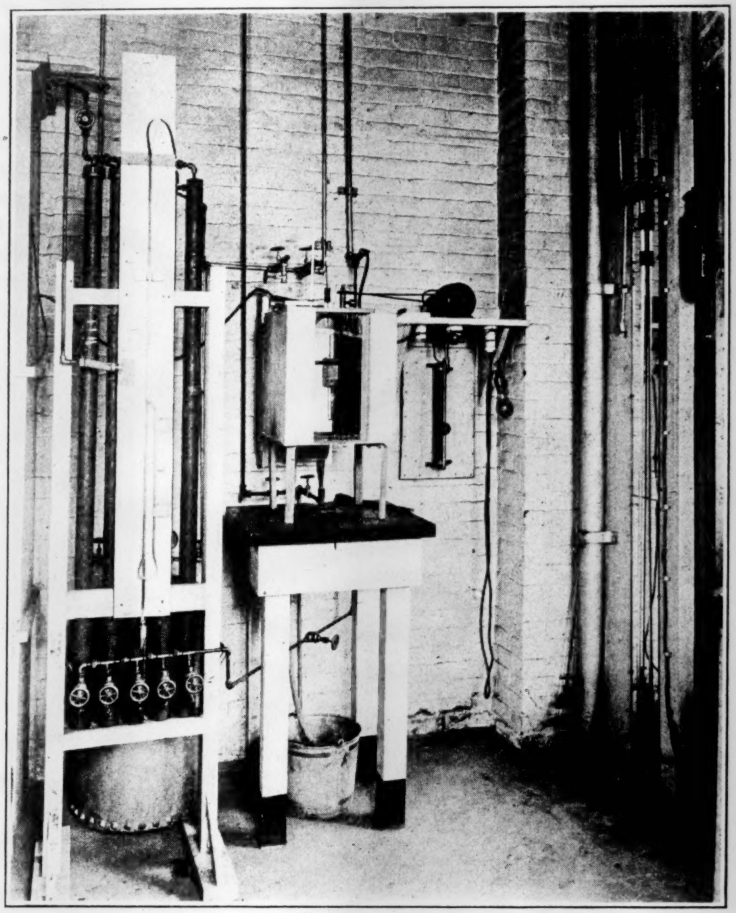

FIG. 4.—The Plastometer, showing Pressure Tank, Stabilizer and Manometer, Container, and an Additional Stabilizer and Water Manometer for Measuring Low Pressures.

The Pressure Regulator and Stabilizer.—This is composed of five stand-pipes, each 5 or 6 ft. high and not less than 2½ in. in diameter. A valve, *K*, for water and a pet-cock, *L*, for drainage, are supplied to each. A glass gage *M* is a very necessary part of the apparatus. In the photograph it is in the back of the instrument and does not show. On the top of the gage is a pet-cock, *P*, opening to the atmosphere. A small air pipe, *N*, reaching nearly to the bottom of the stand-pipe, is connected to the air line at *O*.

The stand-pipes are filled with water to the lower level of the gage, *M*. If sufficient pressure is turned on at *Q* and the pet-cocks, *P*, are closed, air will pass through all five pipes and come out the last one *N*. The pressure will be the sum of the hydrostatic heads in each pipe. If the pet-cock, *P*, is opened, the pressure is the sum of the heads in the first four pipes; if *P* and *P′* are opened the pressure is the sum of the heads in the first three pipes, etc. This gives a means of securing five different pressures without changing the volume of water. If intermediate pressures are required, they are readily obtained by draining off water till the manometer indicates the desired pressure.

During the determination the needle valve, *Q*, is opened just far enough to allow air constantly to bubble through the last pipe. This naturally takes care of any leaks and the pressure will remain perfectly constant, for it depends only on the height of water displaced in the pipes, *N*, *N′*, etc.

The Pressure Tank.—This is not primarily for the purpose of producing the pressure. The actual pressure is constantly supplied through the air line, *R*. Before the determination is started, the container is at atmospheric pressure. When *J* is turned on, there is a sudden rush of the air into the container. This would be sufficient to cause a drop in the manometer were it not for the pressure reservoir. Eventually the manometer would return to its original reading, but in the meantime the determination is under way and the pressure must not be allowed to vary; hence the necessity of a large reservoir, *A*, containing air under the same pressure as in the pipes and manometer. As the volume *A* is large in comparison with the volume of air above the level of the paint in the container, no drop in the manometer will take place.

The Capillary.—The value of K, the capillary constant, depends on the dimensions of the capillary and is

$$K = \frac{8\,l}{\pi\, g\, r^4} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3\ a)^1$$

where l is the length in centimeters, r the radius in centimeters, and g the acceleration of gravity.

The ends of the capillary are ground normal to the axis. It is not necessary to carry it to a polish but the edges must look sharp under a magnification of twenty or thirty diameters. An ordinary vernier calipers capable of reading to 0.001 in. is sufficient to measure the length. As K varies as the fourth power of r, r must be known with great accuracy.

The radius is first obtained by the usual method of mercury calibration. If the bore is circular or very nearly so, this value will be sufficient. This is seldom the case, most capillaries being elliptical. It becomes necessary, then, to correct for ellipticity. To do this we must know the ratio of the average major axis to the average minor axis. A photomicrograph is taken of both ends of the capillary, and on this the center of the bore can be quite accurately located by means of dividers, the major and minor axes found, and then measured. Let m be the ratio of the average minor axis to the average major axis, and R be the radius found by the mercury calibration. Then,

$$R_1 = R\sqrt{m} \text{ and } R_2 = R/\sqrt{m}$$

where R_1 is the average minor radius and R_2 the average major radius. Knowing R_1 and R_2, the following equation[2] gives the average radius for the elliptical bore:

$$r = \frac{2\,R_1^3\,R_2^3}{R_1^2 + R_2^2}$$

The radius, r, must be known to a precision of 0.3 microns at least; the length l, to 25 microns. In mounting the capillary it is cleaned with sulfuric and chromic acids, care being taken

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[1] Bingham, *loc. cit.*

[2] Rücker, *Phil. Trans.* (London), A, 185, p. 438 (1894); Knibbs and Gower, *Proceedings*, Roy. Soc. New South Wales, Vol. 29, 77, p. 10 (1895).

not to touch it at that end which is to be soldered in. It is "tinned" in the usual manner with the low fusion alloy previously mentioned; placed in position and some melted solder poured around it in the small cup, *S*, shown in Fig. 3, *D*. With a little practice very firm mounts can be made.

THE DETERMINATION.

Preparation of Sample.—In order that the rate of flow of the paint through the capillary may not become impaired, all foreign material, such as wood fibers, grit, small pieces of wire, sand, dirt, etc., must be removed.

This is accomplished by straining the sample through a 300-mesh wire screen, rubbing the paint through with the finger tips. Nothing else is necessary in the way of preparation.

Density.—As the volume of flow cannot be obtained very accurately by direct measurement, it must be determined from the weight of flow and the density of the material. It is necessary that the density be known correctly to the third decimal place. This degree of accuracy requires the removal of all occluded air from the sample which is accomplished by stirring in a vacuum (0.1 mm. mercury). Fig. 5 shows a simple device for doing this. The density flask is made from a test-tube and is shown in Fig. 6. There is no graduation on it and the paint is poured in till it reaches the top. The meniscus should be adjusted until it becomes straight across the mouth. The flask holds about 20 cc. It is filled and then suspended in the constant temperature bath while the mobility determination is proceeding. In about 20 minutes it may be removed, a drop of paint added if necessary to straighten up the meniscus, weighed, and the density calculated.

Hydrostatic Head in Container.—The pressure indicated on the manometer is not the total pressure causing flow. The paint in the container and capillary exerts a certain "hydrostatic head" which must be taken into consideration.

The initial head in the container is obtained by measuring the depth of the paint with a straight thin wire. To this is added the length of the capillary which is already known. The sum of these two heads is multiplied by the density of the paint and added to the corrected manometer reading. In place of the weighing tube, *F*, Fig. 3, a longer graduated tube is inserted in *G*, the container placed in the bath and connected with the air pressure.

During the determination there is a drop of hydrostatic head in the container, the exact amount being ascertained from the level of the paint now rising in the graduated tube from below. This tube is calibrated in such a way that the drop in head may be read directly.

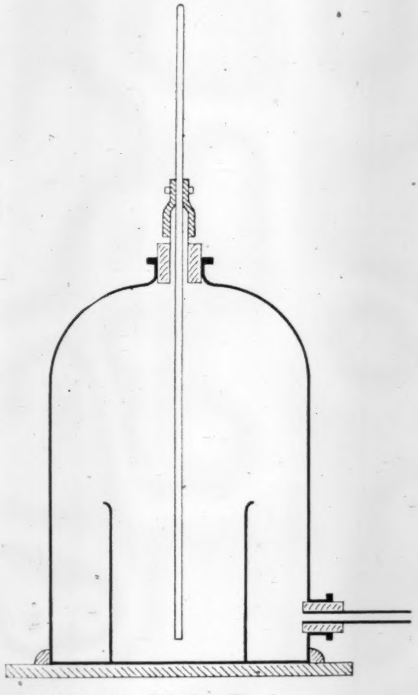

FIG. 5.—Stirring Device.

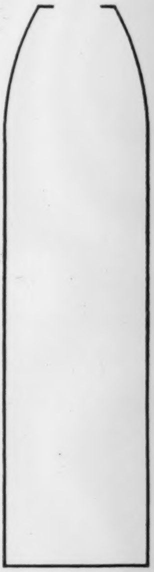

FIG. 6.—Density Flask.

Correction of Pressure.—If the apparatus is constructed so that the middle of the manometer is on a level with the container, the temperature correction is the only one necessary. Table II gives pressure in grams per square centimeter for height in mercurial centimeters. These values are calculated for 20° C. Table III gives the correction for other temperatures.

An example may assist in the use of the tables. Suppose a determination to be made with the manometer reading 56.37 cm. at 16° C. By interpolation in Table II we find the pressure to be 763.5 g. per sq. cm., but by Table III there is, at 16° C., a correction of 0.6 to be added, making a pressure of 764.0.

Volume of Flow.—As previously mentioned the volume of flow is not obtained from direct measurement, but by dividing the weight of flow by the density of the paint. Use is made of the fact that under a given rate of flow the weight of a drop falling from the end of the capillary is constant. If we know this weight (which varies with different paints), the number of such drops extruded in a certain time, and the density, it is easy to calculate the volume of flow per second.

Change in Weight of Drop.—The weight of a drop changes with the rate of flow. The greater the rate, the larger the drop. Thus,[1]

$$\text{Weight of drop} = (C \times \text{rate of flow}) + C'.$$

If we are determining, say, six points on the curve it is necessary to know the weight of drop only under the highest and lowest rates of flow. The four intermediate weights are found by interpolation.

How the Plastometer is Used.—It is usually convenient to commence with the highest pressure, the magnitude of which will depend on the speed of the capillary used; a drop every five seconds is not too fast.

The container is filled with paint to within a centimeter of the top and allowed to remain in the bath for 20 minutes so that it attains the required temperature. For all determinations given in this paper, 20° C. has been used. In the meantime the stabilizer is adjusted. The three-way stop-cock is now turned so that the pressure enters the container. A reliable stop-watch may be used to record the time of flow, which should never be less than 100 seconds. Repeat the measurement until it checks to within 0.3 seconds. Fractions of drops are avoided. The watch is started the instant a preliminary drop—which is not counted—detaches itself; it is stopped the instant the last drop falls. This gives a sharp beginning and end point.

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[1] The experimental demonstration of this fact will appear in a later paper.

TABLE II.—PRESSURES IN GRAMS PER SQUARE CENTIMETER, FOR HEIGHTS IN MERCURIAL CENTIMETERS.

Height, cm. Hg.	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
10	135.4	36.8	38.2	39.5	40.9	42.2	43.6	44.9	46.3	47.6
11	49.0	50.3	51.7	53.1	54.4	55.8	57.1	58.5	59.8	61.2
12	62.5	63.9	65.2	66.6	68.0	69.3	70.7	72.0	73.4	74.7
13	76.1	77.4	78.8	80.1	81.5	82.9	84.2	85.6	86.9	88.3
14	89.6	91.0	92.3	93.7	95.0	96.4	97.8	99.1	*00.5	*01.8
15	203.2	04.5	05.9	07.2	08.6	09.9	11.3	12.7	14.0	15.4
16	16.7	18.1	19.4	20.8	22.1	23.5	24.8	26.2	27.6	28.9
17	30.3	31.6	33.0	34.3	35.7	37.0	38.4	39.7	41.1	42.5
18	43.8	45.2	46.5	47.9	49.2	50.6	51.9	53.3	54.6	56.0
19	57.4	58.7	60.1	61.4	62.8	64.1	65.5	66.8	68.2	69.5
20	70.9	72.2	73.6	75.0	76.3	77.7	79.0	80.4	81.7	83.1
21	84.4	85.8	87.2	88.5	89.9	91.2	92.6	93.9	95.3	96.6
22	98.0	99.3	*00.7	*02.0	*03.4	*04.8	*06.1	*07.5	*08.8	*10.2
23	311.5	12.9	14.2	15.6	16.9	18.3	19.7	21.0	22.4	23.7
24	25.1	26.4	27.8	29.1	30.5	31.8	33.2	34.6	35.9	37.3
25	38.6	40.0	41.3	42.7	44.0	45.4	46.7	48.1	49.5	50.8
26	52.2	53.5	54.9	56.2	57.6	58.9	60.3	61.6	63.0	64.4
27	65.7	67.1	68.4	69.8	71.1	72.5	73.8	75.2	76.5	77.9
28	79.2	80.6	82.0	83.3	84.7	86.0	87.4	88.7	90.1	91.4
29	92.8	94.2	95.5	96.9	98.2	99.6	*00.9	*02.3	*03.6	*05.0
30	406.3	07.7	09.1	10.4	11.8	13.1	14.5	15.8	17.2	18.5
31	19.9	21.2	22.6	24.0	25.3	26.7	28.0	29.4	30.7	32.1
32	33.4	34.8	36.1	37.5	38.9	40.2	41.6	42.9	44.3	45.6
33	47.0	48.3	49.7	51.0	52.4	53.7	55.1	56.5	57.8	59.2
34	60.5	61.9	63.2	64.6	65.9	67.3	68.6	70.0	71.4	72.7
35	74.1	75.4	76.8	78.1	79.5	80.8	82.2	83.5	84.9	86.3
36	87.6	89.0	90.3	91.7	93.0	94.4	95.7	97.1	98.4	99.8
37	501.2	02.5	03.9	05.2	06.6	07.9	09.3	10.6	12.0	13.3
38	14.7	16.1	17.4	18.8	20.1	21.5	22.8	24.2	25.5	26.9
39	28.2	29.6	31.0	32.3	33.7	35.0	36.4	37.7	39.1	40.4
40	41.8	43.1	44.5	45.9	47.2	48.6	49.9	51.3	52.6	54.0
41	55.3	56.7	58.0	59.4	60.8	62.1	63.5	64.8	66.2	67.5
42	68.9	70.2	71.6	72.9	74.3	75.6	77.0	78.4	79.7	81.1
43	82.4	83.8	85.1	86.5	87.8	89.2	90.5	91.9	93.3	94.6
44	96.0	97.3	98.7	*00.0	*01.4	*02.7	*04.1	*05.4	*06.8	*08.2
45	609.5	10.9	12.2	13.6	14.9	16.3	17.6	19.0	20.3	21.7
46	23.1	24.4	25.8	27.1	28.5	29.8	31.2	32.5	33.9	35.2
47	36.6	38.0	39.3	40.7	42.0	43.4	44.7	46.1	47.4	48.8
48	50.1	51.5	52.9	54.2	55.6	56.9	58.3	59.6	61.0	62.3
49	63.7	65.0	66.4	67.8	69.1	70.5	71.8	73.2	74.5	75.9
50	77.2	78.6	79.9	81.3	82.6	84.0	85.4	86.7	88.1	89.4
51	90.8	92.1	93.5	94.8	96.2	97.5	98.9	*00.3	*01.6	*03.0
52	704.3	05.7	07.0	08.4	09.7	11.1	12.4	13.8	15.2	16.5
53	17.9	19.2	20.6	21.9	23.3	24.6	26.0	27.3	28.7	30.1
54	31.4	32.8	34.1	35.5	36.8	38.2	39.5	40.9	42.2	43.6
55	45.0	46.3	47.7	49.0	50.4	51.7	53.1	54.4	55.8	57.1
56	58.5	59.9	61.2	62.6	63.9	65.3	66.6	68.0	69.3	70.7
57	72.0	73.4	74.7	76.1	77.5	78.8	80.2	81.5	82.9	84.2
58	85.6	86.9	88.3	89.6	91.0	92.4	93.7	95.1	96.4	97.8
59	99.1	*00.5	*01.8	*03.2	*04.5	*05.9	*07.3	*08.6	*10.0	*11.3
60	812.7	14.0	15.4	16.7	18.1	19.4	20.8	22.2	23.5	24.9
61	26.2	27.6	28.9	30.3	31.6	33.0	34.3	35.7	37.1	38.4
62	39.8	41.1	42.5	43.8	45.2	46.5	47.9	49.2	50.6	52.0
63	53.3	54.7	56.0	57.4	58.7	60.1	61.4	62.8	64.1	65.5
64	66.8	68.2	69.6	70.9	72.3	73.6	75.0	76.3	77.7	79.0
65	80.4	81.7	83.1	84.5	85.8	87.2	88.5	89.9	91.2	92.6
66	93.9	95.3	96.6	98.0	99.4	*00.7	*02.1	*03.4	*04.8	*06.1
67	907.5	08.8	10.2	11.5	12.9	14.3	15.6	17.0	18.3	19.7
68	21.0	22.4	23.7	25.1	26.4	27.8	29.2	30.5	31.9	33.2
69	34.6	35.9	37.3	38.6	40.0	41.3	42.7	44.1	45.4	46.8

TABLE II.—*Continued.*

Height, cm. Hg.	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
70	48.1	49.5	50.8	52.2	53.5	54.9	56.2	57.6	58.9	60.3
71	61.7	63.0	64.4	65.7	67.1	68.4	69.8	71.1	72.5	73.8
72	75.2	76.6	77.9	79.3	80.6	82.0	83.3	84.7	86.0	87.4
73	88.7	90.1	91.5	92.8	94.2	95.5	96.9	98.2	99.6	*00.9
74	1002.3	03.6	05.0	06.4	07.7	09.1	10.4	11.8	13.1	14.5
75	15.8	17.2	18.5	19.9	21.2	22.6	24.0	25.3	26.7	28.0
76	29.4	30.7	32.1	33.4	34.8	36.1	37.5	38.9	40.2	41.6
77	42.9	44.3	45.6	47.0	48.3	49.7	51.0	52.4	53.8	55.1
78	56.5	57.8	59.2	60.5	61.9	63.2	64.6	65.9	67.3	68.7
79	70.0	71.4	72.7	74.1	75.4	76.8	78.1	79.5	80.8	82.2
80	83.6	84.9	86.3	87.6	89.0	90.3	91.7	93.0	94.4	95.7
81	97.1	98.4	99.8	*01.2	*02.5	*03.9	*05.2	*06.6	*07.9	*09.3
82	1110.6	12.0	13.3	14.7	16.1	17.4	18.8	20.1	21.5	22.8
83	24.2	25.5	26.9	28.2	29.6	31.0	32.3	33.7	35.0	36.4
84	37.7	39.1	40.4	41.8	43.1	44.5	45.9	47.2	48.6	49.9
85	51.3	52.6	54.0	55.3	56.7	58.0	59.4	60.7	62.1	63.5
86	64.8	66.2	67.5	68.9	70.2	71.6	72.9	74.3	75.6	77.0
87	78.4	79.7	81.1	82.4	83.8	85.1	86.5	87.8	89.2	90.5
88	91.9	93.3	94.6	96.0	97.3	98.7	*00.0	*01.4	*02.7	*04.1
89	1205.4	06.8	08.2	09.5	10.9	12.2	13.6	14.9	16.3	17.6
90	19.0	20.3	21.7	23.1	24.4	25.8	27.1	28.5	29.8	31.2
91	32.5	33.9	35.2	36.6	37.9	39.3	40.7	42.0	43.4	44.7
92	46.1	47.4	48.8	50.1	51.5	52.8	54.2	55.6	56.9	58.3
93	59.6	61.0	62.3	63.7	65.0	66.4	67.7	69.1	70.5	71.8
94	73.2	74.5	75.9	77.2	78.6	79.9	81.3	82.6	84.0	85.4
95	86.7	88.1	89.4	90.8	92.1	93.5	94.8	96.2	97.5	98.9
96	1300.2	01.6	03.0	04.3	05.7	07.0	08.4	09.7	11.1	12.4
97	13.8	15.1	16.5	17.9	19.2	20.6	21.9	23.3	24.6	26.0
98	27.3	28.7	30.0	31.4	32.8	34.1	35.5	36.8	38.2	39.5
99	40.9	42.2	43.6	44.9	46.3	47.7	49.0	50.4	51.7	53.1
100	54.4	55.8	57.1	58.5	59.8	61.2	62.5	63.9	65.3	66.6
200	2708.7	10.0	11.4	12.7	14.1	15.5	16.8	18.2	19.5	20.9
300	4062.8	64.2	65.5	66.9	68.2	69.6	71.0	72.3	73.7	75.0

If a satisfactory check has been obtained, the fall in hydrostatic head is observed and the pressure changed to a lower one. The same procedure is repeated as many times as points on the curve are desired. The container is then removed from the bath and a weighing tube inserted in place of the graduated tube. The container is replaced and any convenient number of drops taken under the last pressure used. These are weighed and the weight of one drop determined. The same is done with the highest pressure. Weights of the intermediate drops are interpolated between the two. To do this it is necessary to plot *pressure* and not rate of flow, against weight of drop. This is permissible on account of the fact that pressure and rate of flow bear a linear relationship to each other. The necessity of weighing all the intermediate drops is thus eliminated.

Determining Mobility and Yield Value.—As the yield value is that pressure below which no flow takes place, it is immaterial whether weight or volume per second is plotted against pressure in order to obtain it. By plotting the former some unnecessary calculations are avoided.

TABLE III.—CORRECTION IN PRESSURES (GRAMS PER SQUARE CENTIMETER) FOR VARIOUS TEMPERATURES AND MERCURIAL HEIGHTS.

Temperature, deg. Cent.	Height of Mercury, cm.									
	10	20	30	40	50	60	70	80	90	100
5	0.4	0.7	1.1	1.5	1.8	2.2	2.6	2.9	3.3	3.7
6	0.3	0.7	1.0	1.4	1.7	2.1	2.4	2.7	3.1	3.4
7	0.3	0.6	1.0	1.3	1.6	1.9	2.2	2.6	2.9	3.2
8	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.6	2.9
9	0.3	0.5	0.8	1.1	1.4	1.6	1.9	2.2	2.4	2.7
10	0.2	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.2	2.4
11	0.2	0.4	0.7	0.9	1.1	1.3	1.5	1.8	2.0	2.2
12	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
13	0.2	0.3	0.5	0.7	0.9	1.0	1.2	1.4	1.5	1.7
14	0.2	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3	1.5
15	0.1	0.2	0.4	0.5	0.6	0.7	0.9	1.0	1.1	1.2
16	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
17	0.1	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.7
18	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5
19	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2
22	-0.1	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.5
23	-0.1	-0.1	-0.2	-0.3	-0.4	-0.4	-0.5	-0.6	-0.7	-0.7
24	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0
25	-0.1	-0.2	-0.4	-0.5	-0.6	-0.7	-0.9	-1.0	-1.1	-1.2
26	-0.2	-0.3	-0.4	-0.6	-0.7	-0.9	-1.0	-1.2	-1.3	-1.5
27	-0.2	-0.3	-0.5	-0.7	-0.9	-1.0	-1.2	-1.4	-1.5	-1.7
28	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4	-1.6	-1.8	-2.0
29	-0.2	-0.4	-0.7	-0.9	-1.1	-1.3	-1.5	-1.8	-2.0	-2.2
30	-0.2	-0.5	-0.7	-1.0	-1.2	-1.5	-1.7	-2.0	-2.2	-2.4
31	-0.3	-0.5	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2	-2.4	-2.7
32	-0.3	-0.6	-0.9	-1.2	-1.5	-1.8	-2.1	-2.4	-2.6	-2.9
33	-0.3	-0.6	-1.0	-1.3	-1.6	-1.9	-2.2	-2.6	-2.9	-3.2
34	-0.3	-0.7	-1.0	-1.4	-1.7	-2.1	-2.4	-2.7	-3.1	-3.4
35	-0.4	-0.7	-1.1	-1.5	-1.8	-2.2	-2.6	-2.9	-3.3	-3.7

If weight is used instead of volume of flow, the density must be introduced into the mobility equation:

$$\mu = \frac{K\,W}{\rho\,(P-f)} \qquad (4)$$

where W is the weight of flow per unit of time and ρ is the density.

EXPERIMENTAL RESULTS.

Laboratory Data.—In presenting the results of our preliminary work in this paper our object is two-fold: first, to give substantial evidence that the plastometer is of practical importance to the paint chemist in his every-day laboratory work; and, secondly, to show that it is an instrument of unlimited possibilities, not only for investigating the laws of plastic flow but also for investigating the many research problems which constantly present themselves to the paint investigator.

In Fig. 2 we have an expression of the fundamental principle underlying plastic flow. In actual practice we find that when using low pressures there is an apparent deviation from this law, that is, the relationship between P and V is no longer linear and the curve gradually falls off toward the origin. If seepage[1] takes place, as it would be natural to expect under such a condition, this phenomenon as well as another to be mentioned later, is easily accounted for. Be that as it may, our results are in no way influenced by this anomaly if low pressures be avoided and, therefore, we leave its discussion for a future paper.

TABLE IV.—PROPERTIES OF THE VARIOUS CAPILLARIES.

No.	Radius, r, cm.	Length, l, cm.	K.	Speed.
IV	0.031365	3.162	8 498	**Very fast.**
VII	0.034587	4.711	8 553	**Very fast.**
II	0.031381	4.681	12 540	**Fast**
V	0.031388	5.973	15 986	**Fast**
VIII	0.031402	7.605	20 319	Medium.
III	0.024500	4.681	33 752	Medium.
VI	0.021839	4.684	64 954	Slow.
IX	0.014610	1.565	89 230	Slow.
S	0.014486	4.620	272 514	Very slow.

It will be necessary to refer occasionally to the various capillaries used. They are listed in Table IV.

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[1] *Scientific Paper No. 278*, U. S. Bureau Standards 12, p. 326 (1916).

In Fig. 7 the general form of the curve for three different capillaries, using the same paint for each capillary, is given. The laboratory measurements are given in Table V. An analysis of the experimental results indicates:

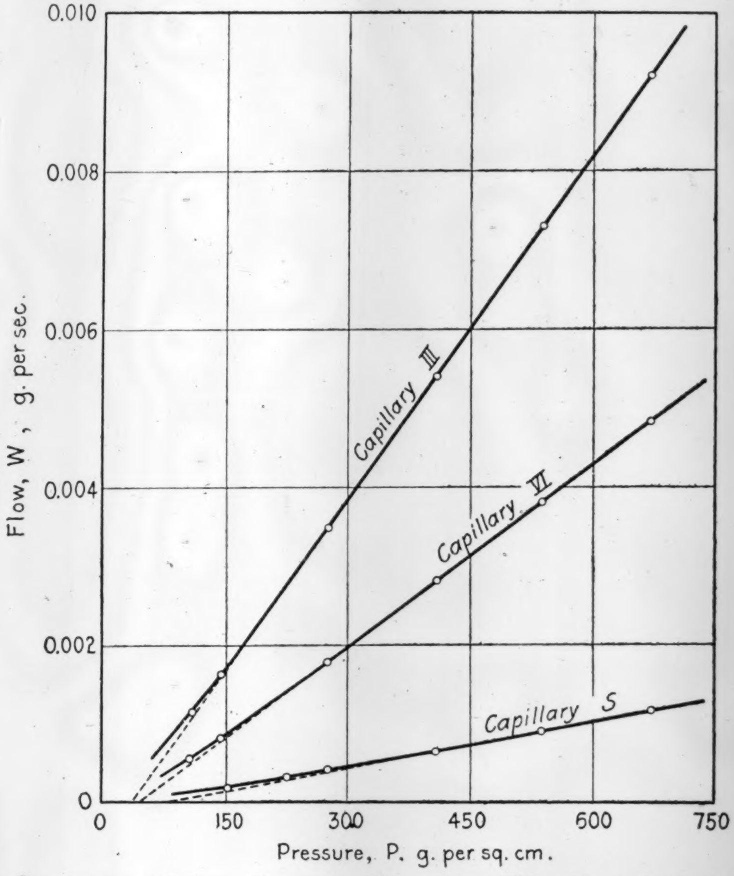

FIG. 7.—Pressure-Volume Curves for Given Paint, Using Three Capillaries.

1. That the degree of accuracy of the plastometer itself is satisfactorily high. This is evident when we examine the results from any one capillary. Of the three, capillary VI contains the largest divergency from its average. This particular error is only 0.28 per cent.

2. That the slower the capillary the larger the yield value. The yield value, therefore, is apparently a function of the capillary as well as some inherent property of the paint.

3. That the apparent value of the mobility is not a constant for different capillaries, but varies directly with the yield value. If seepage takes place, we would naturally expect its effect to become more noticeable as we go to capillaries of smaller bore, that is, slower ones. This is evidently what happens, giving rise to a higher mobility than normally would be expected.

TABLE V.—DETERMINATION OF MOBILITY AND YIELD VALUE OF GIVEN PAINT WITH DIFFERENT CAPILLARIES. SEE FIG. 7.

DENSITY = 1.986.

Pressure, g. per sq. cm.	Time, seconds.	Weight, g.	$\frac{\text{Weight}}{\text{Time}}$, W.	Mobility, μ.	Yield Value, f.
		CAPILLARY S.			
670.8	116.3	0.13480	0.0011591	0.2621	64
537.8	118.3	0.10716	0.0009050	0.2621	
409.3	160.3	0.10648	0.0006642		
277.5	187.0	0.07941	0.0004237		
225.6	160.0	0.05278	0.0003299		
152.9	130.0	0.02630	0.0002023		
		CAPILLARY VI.			
670.2	79.9	0.3847	0.004815	0.2519	42
538.5	99.8	0.3789	0.003797	0.2517	
409.5	110.4	0.3110	0.002817	0.2528	
274.3	120.0	0.2142	0.001785		
143.3	145.6	0.1204	0.000827		
106.7	104.7	0.0598	0.000572		
		CAPILLARY III.			
671.7	86.3	0 7950	0.009212	0.2451	33
539.1	85.3	0.6230	0.007304	0.2453	
409.0	84.5	0.4575	0.005414	0.2447	
275.6	102.5	0.3579	0.003492	0.2446	
145.1	124.3	0.2041	0.001642		
110.0	99.6	0.1159	0.001163		

We can infer from the last statement that the "faster" the capillary, the nearer the mobility will be to its true value. If this is so, we have a simple means at hand for making seepage correction. Before doing so, however, it will be necessary to learn something more definite about the nature of the pressure-volume curve.

The form of the curve is that of an hyperbola with its vertex at the origin:

$$P^2 = AW^2 + BW \qquad \text{.................. (5)}$$

This being the case we must make sure that we are using the "straight" part of the curve, that is, where P and W bear a linear relationship. It is possible to do so by making the calculations from the asymptote. Where the yield value is low (under 75 g.), this is unnecessary, for the asymptote and the tangent to the curve at the highest pressures are usually coincident.

There are paints, however, where the yield values are much higher, and we must resort to the use of the asymptote.

Eq. 5 may be written:

$$P = (AW^2 + BW)^{\frac{1}{2}}$$

then,

$$\frac{\delta W}{\delta P} = \frac{2\sqrt{A + \dfrac{B}{W}}}{2A + \dfrac{B}{W}}$$

When W approaches infinity, $\dfrac{\delta W}{\delta P}$ becomes the slope of the asymptote, or $\dfrac{1}{\sqrt{A}}$; therefore,

$$\mu = \frac{K}{\rho\sqrt{A}} \qquad \text{...................... (6)}$$

The equation of a line through any point P, W, on the hyperbola and parallel to the asymptote is,

$$\frac{W}{P - f} = \frac{1}{\sqrt{A}} \qquad \text{.................... (7)}$$

From Eq. 5,

$$\frac{1}{\sqrt{A}} = \frac{W}{\sqrt{P^2 - BW}}$$

Substituting in Eq. 7,

$$P - f = \sqrt{P^2 - BW}$$

or

$$P^2 - 2\,Pf + f^2 = P^2 - B\,W$$
$$2\,Pf - f^2 = BW$$

When P and W become infinitely great, f reaches a constant value, then,

$$2\,f\delta P = B\delta W$$

or

$$\frac{\delta W}{\delta P} = \frac{2\,f}{B}$$

At infinity,

$$\frac{\delta W}{\delta P} = \frac{1}{\sqrt{A}}$$

Therefore

$$f = \frac{B}{2\,\sqrt{A}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Any two points on the curve may be used to determine the constants A and B, but it is better to avoid the lower pressures as the experimental error here is liable to be appreciable.

$$A = \frac{\frac{P_1^2}{W_1} - \frac{P_2^2}{W_2}}{W_1 - W_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$B = \frac{P_1^2}{W_1} - A\,W_1 \quad \ldots\ldots\ldots\ldots\ldots (10)$$

As to the most acceptable means for making a seepage correction, the authors are not in a position to say what it will be at this early stage of the work. No doubt a number of ways can be worked out. A graphical method has been used with success. In Fig. 8, mobility has been plotted against yield value. We know that as the yield value rises, the effect of seepage on the mobility increases; hence it is evident that the intercept gives the true value for the mobility. This may easily be misunderstood. We are not to infer that there will be no yield value for the true mobility, but only that the effect of seepage arising from a finite yield value becomes zero at this point.

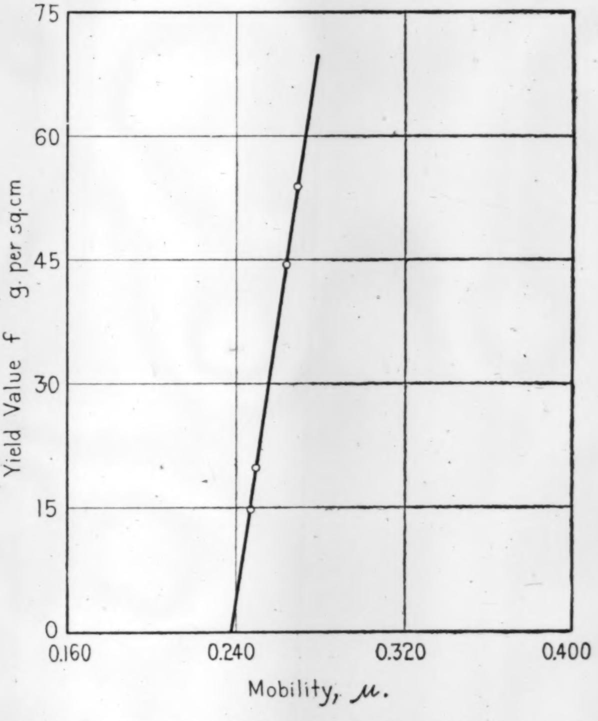

FIG. 8.—Relation between Mobility and Yield Value, derived from Asymptotes of Pressure-Volume Curves.

In Table VI are given the experimental data for Fig. 8. The values plotted are those derived from the asymptotes. If this had not been the case the relationship between f and μ would cease to be linear and there would be no way of ascertaining the true mobility.

TABLE VI.—EXPERIMENTAL DATA FOR FIG. 8.

Capillary	Calculated from the Tangent		Calculated from the Asymptote	
	μ	f	μ	f
S	0.266	45	0.270	53.8
V	0.261	37	0.265	44.5
IX	0.252	21	0.250	20.0
IV	0.248	15	0.247	14.8

In Table VII are the mobilities and yield values for some ready mixed paints.

TABLE VII.—MOBILITIES AND YIELD VALUES OF THREE PAINTS.

CAPILLARY III.

	μ	f
No. 1. Straight ZnO	0.204	87
No. 2. Zinc and Lead	0.373	320
No. 3. C. W. Lead	0.174	117

Discussion.—With the facts now before us we are able to judge of the various merits and demerits of our work. When we realize the ease with which the technical viscosimeters in use today will turn out "viscosity" determinations, we are liable to have some misgiving as to the practicability of our method. However, we are now fully aware of the fact that paint is a plastic material and, therefore, none of the technical viscosimeters is able to determine its mobility or anything running parallel to it.

This is clearly exemplified in Table VII. With any short-tube technical viscosimeter paint No. 2, on account of its high yield value, would be accorded the greatest viscosity. As a matter of fact it actually is the most mobile of the three. Paint No. 3, due to its high density, will run with greater ease than No. 1, therefore, it would naturally be given the smallest viscosity. In reality it is the least mobile of any. Furthermore, this type of viscosimeter will not give a comparison of the yield values; for in this case it would place No. 3 before No. 1. It is evident that no matter what type of technical viscosimeter is used, at the best it can give nothing more than a sort of hybrid result depending on the properties imparted to the paint by both its mobility and yield value.

A good pipe-fitter and mechanic can make the entire apparatus with the exception of mounting and calibrating the capillary. This must be done by the investigator himself or any one else suitably trained.

Calculating the constants of the hyperbola is perhaps somewhat tedious but otherwise the formulas are not unwieldy. The kinetic energy correction is quite negligible and may be omitted in all cases. Its value is $\frac{MW}{8\pi lt}$, where M is a constant and is generally accepted to be 1.12.[1] This correction is to be subtracted from the rigidity and not from the mobility. The mobility is then obtained by taking the reciprocal of the corrected rigidity. For research work of an exacting nature the calculations must be made with logarithms or a calculating machine, but for routine work the slide rule is quite accurate enough.

We have measured pastes with a mobility as low as 0.000400 and paints as high as 0.750. This gives some idea as to the ample range over which the measurements may extend. An error of 10 or 20 per cent is not, under such circumstances, a very serious matter; yet the error is less than 1 per cent.

So far, we have not been able to develop a method whereby the exact mobility can be obtained from one capillary only. Yield values also are comparable only when determined with the same capillary. The solution of these problems, however, is but a matter of time and according to present indications should offer no very unusual difficulties.

Having once established, on a substantial scientific basis, a method for measuring the resistances to flow, we have in our possession a means of investigating intelligently such subjects as, for instance, oil absorption of pigments, thickening and thinning of paint, livering and the various colloidal phenomena often associated with paint. Furthermore, we can set up for ourselves standards which the manufactured products must meet, and thus obtain a more rational method for their control than the usual rule-of-thumb procedures often encountered in the pigment and paint industries.

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[1] *Zeit. physikalische Chemie,* Vol. 80, p. 681 (1912).

CONCLUSIONS.

In setting forth the results of our work in its present elementary state of development the authors have been ever mindful that the final establishment of a law is invariably a matter of time, backed by the evidence of gradually accumulated experimental data. We have presented results of our investigations to date in such a manner as to cause the most important features to stand out in relief. Many hundreds of experiments have been omitted and interesting investigations of a subsidiary nature have not been mentioned at all. When these are reported, we hope to show that the mobility and the yield value are thoroughly characteristic, definite and accurately measurably properties.

The laws of plastic flow are basicly sound and may be accepted without hesitancy on the part of the investigator. At the most, the future can do little more than amplify them, leaving them substantially the same as we have endeavored to present them in this paper.

In concluding we wish to express our appreciation for the many helpful suggestions and kind assistance received from the members of our Research Department.

DISCUSSION.

Mr. Thompson.

MR. G. W. THOMPSON (*presented in written form*).—This paper is fully up to the standard of the several papers on related subjects to which Mr. Bingham has attached his name. It marks a distinct advance in the study of the physical properties of mixtures of fine particles with liquids, particularly such as may be described as paints.

In this paper the authors lay down the postulate that paint is a plastic material and not a viscous liquid. They may be right in this postulate, but it deserves some consideration before it is fully accepted. According to the definition laid down by this Society, paint is "a mixture of pigment with vehicle intended to be spread in thin coats for decoration or protection or both." According to this definition the volume of concentration of the pigment is not specified. This volume concentration may be small or great, so long as that concentration is appreciable. It would appear, therefore, that the title of the paper under discussion is, strictly speaking, incorrect, because there are mixtures of pigment and vehicle which follow the laws of viscous flow, although such mixtures may not be practical paints. It would seem, furthermore, that most paints thinned for the priming of wood probably follow the laws of viscous flow, as the volume of concentration of the pigment in these priming paints is not great enough to reach what has been described as "zero fluidity." The fact, however, that the title of this paper may not, strictly speaking, be accurate, does not at all impair its value.

If there is any point in which I am dissatisfied with this paper it is that it does not go far enough. I consider this dissatisfaction, however, as complimentary to the paper. One line of information that would be very valuable, which the paper indicates it is possible to obtain, but which the paper does not disclose, is this: It would seem possible that with various mixtures of pigment and vehicle there would be two kinds of flow; where the volume concentration of the pigment is relatively low, we have viscous flow; where the volume concentration

Mr. Thompson. of the pigment is relatively high, we have plastic flow. If it is possible to plot curves for these two kinds of flow, it ought also to be possible to combine the curves and show graphically the kind of information which I have stated is indicated in this paper but not disclosed. Thus, in the case of a certain series of mixtures varying simply in concentration, if the flow is made constant one should be able to plot the pressure against concentration. Such a curve would show the concentration corresponding to zero fluidity. The slope of the lines on either side of this point would, very probably, give valuable practical information.

The authors state that as a result of their study they "are now in a position to predict the nature of a paint, knowing its mobility and yield value." I think this statement is correct as far as it goes. The implication, however, that a paint having a low mobility and a high yield value will of necessity be a good paint, is one that must be taken with a grain of salt. A high yield value, in the case of paint, may mean a paint that will not flow out; that is, a paint that will show brush marks excessively. It would appear, therefore, that their statement has limits and it would be more accurate to say that a paint with a low mobility and high yield value, between certain limits, is a good paint, etc.

These questions, therefore, present themselves:

Do not paints, under some conditions, have a volume concentration less than zero fluidity?

Would it be possible to plot the curve indicated above, showing concentration plotted against pressure, with the flow constant?

Is it not true that a yield value can be too high, considering the flowing qualities of paint?

Mr. Bingham. MR. E. C. BINGHAM.—I was very much interested in the discussion that Mr. Thompson has given us. It seems to me that the points he has raised are of great value, and they have not, for the most part, occurred to us. In this paper it did not seem best to take up more than one point that we wanted to drive home, namely, the practicability of measuring these two quantities, the yield value and the mobility, and emphasizing the fact that they exist.

We have been doing some work which will be published in a subsequent paper on the Viscosity of Thin Paints. We understood, in the title of the paper, that by paints was meant practicable paints or thick paints as distinguished from pastes, which ordinarily would be thought of as plastic materials and not paints. **Mr. Bingham.**

It seems to me that the great advantage is to have a precise method of measurement, and our paper does demonstrate that we can measure these two quantities with precision. Having two quantities that we can measure with precision, it seems to me that progress in paint technology, in ceramics and in various other fields is almost certain.

Mr. Herschel. MR. WINSLOW H. HERSCHEL (*presented in written form*).—This paper marks a noteworthy advance in our knowledge of plastic materials and should lead to a much clearer understanding of the subject. It raises the question whether grease is a plastic substance and whether the determination of consistency by ordinary viscosity methods may not be misleading.

It is stated in the paper that the edges at the ends of the bore of a capillary must look sharp under a magnification of twenty or thirty diameters. I have found difficulty in obtaining this result and would inquire what method was used. If the ends of the capillary are filled with wax when ground, what is the best kind of wax to preserve the sharpness of the edges and yet be easily removable?

It is not clear whether it is concluded on theoretical or experimental ground that the curve corresponding to Eq. 5 is that of an hyperbola with its vertex at the origin; and the whole question of seepage is left for future investigation.

It is stated that the yield value is apparently a function of the capillary, and it is assumed that this is due to variations in seepage with the speed or bore. It does not seem clear that the variation in yield value may not depend to some extent upon the variation in ratio of length to diameter, l/d. Further investigation may be necessary, using capillaries having the same value of K or of l/d, to determine which value is influential in fixing the yield value. For the three capillaries of Fig. 7, the values of l/d are 96, 107 and 159.

Does the phrase "as the yield rises" refer to an increase in the yield value due to changes in capillary or to changes in paint with the same capillary?

Mr. Herschel. While the true value of the mobility is explained, the paper does not appear to show how the true value of the yield value may be obtained.

Mr. Green. MR. HENRY GREEN.—As to Mr. Herschel's inquiries: Eq. 5, $P^2=AW^2+BW$, is empirical. The experimentally determined points, however, agree with great accuracy with those calculated from the equation. The difference between them is less than the experimental error.

As to the variation in yield value, let me say that yield value, first of all, is a function of the paint, of course, but it will vary with the capillary used; the smaller the radius, the higher the yield value; the longer the length, the greater, to a slight extent, the yield value; but it varies most effectively with the radius.

As to the method of determining yield value, we have not referred to that. The only method we had was one of comparison. If you wish to compare yield values, the same capillary must be employed each time. We have not, up to the present, worked out a method by which yield values can be reduced to a common basis.

Mr. Bingham. MR. BINGHAM.—Mr. Herschel has referred to the variation in yield value. I might state that we have worked out a very precise relationship between radius, length and yield value, which will be described in a subsequent paper.

Mr. Herschel. MR. HERSCHEL.—But that seems to introduce three variables instead of two. The paper refers to speed. Speed depends on the two values, radius and length, and you do not bring out which is the essential thing.

Mr. Green. MR. GREEN.—The radius is the more essential of the two, but the yield value will vary with both radius and length, as you suggested. It is simply a matter of the capillary constant; the greater the capillary constant, the greater will be the yield value. The capillary constant takes care of both of those variables.

Mr. Breyer. MR. F. G. BREYER.—The variable yield values found by Bingham and Green with different sized capillaries (giving different rates of flow) seem to me to be best explained by the assumption that the yield value in plastic materials is not a constant but dependent upon the rate of application of load. I cannot

Mr. Breyer. agree with Mr. Bingham that at low rates of flow the gradual deviation of the curves from the straight line toward the origin is due to seepage or any similar phenomena, but am convinced that at low rates of load application the material becomes less and less a plastic one and more and more nearly a true liquid. In other words, there is no sharp dividing line between true solids and true liquids, the determining factor, yield value, varying from zero at very slow rates of loading up to quite high figures when the rate of loading is rapid for even so plastic a material as paint, as shown by Bingham and Green.

I have had occasion to notice this same condition of varying yield value in a very less plastic material than paint and one which we do not ordinarily think of as plastic at all, namely, rolled zinc. Within very reasonable limits of rate of load application, high-grade rolled zinc will vary in all its mechanical properties quite markedly. For example, with a rapid application of load such as we get when the scleroscope hammer hits the surface of zinc a high yield value or hardness figure is obtained. When this same material is tested in an ordinary tensile machine where the loading is for a period of minutes, we have been unable so far to apply any load that did not produce a flow of the metal.

The use of the plastometer in the study of paints is but one of its many possibilities. The entire field of colloid chemistry, where paint pigment suspensions in vehicles properly belong, will welcome this instrument, since perhaps the most characteristic property of colloids is their effect upon the viscosity, or more generally, upon the plasticity of matter in which they are present. So far we have had no instrument for measuring the "set" of pastes, livers and jells, excepting when these possessed very marked solid properties, that is to say, relatively high yield value such as can be measured by refinement of the ordinary mechanical testing principles.

Mr. Parks. MR. G. E. PARKS.—I should like to ask Mr. Green a question in regard to the viscosity tests. If two samples of a given paint are ground, one to a very high degree of fineness, and the other rather coarsely, and the two samples mixed with different amounts of linseed oil, would the tests described in the paper indicate the same viscosity for the two mixtures, or would they show up the difference in the fineness of grinding of the two samples?

Mr. Green. MR. GREEN.—We have never made such an experiment, but I can guess what the results will be, if you will be satisfied with a guess. I think the mobilities would be the same in both cases, but the yield values would be different; the finer the particles, the higher the yield value.

Mr. Gardner. MR. H. A. GARDNER.—I think this is one of the most interesting papers we have had before the Society, and I think it would be well to make a practical application of it. If we might have had this knowledge four or five years ago, different results would have been obtained from some of the tests made at Arlington. At that time a lot of paints were made in paste form, put through a Stormer viscosimeter and then thinned down with linseed oil until they all apparently had the same viscosity. The determinations were fallacious. What was actually done was to make some paints of a very low and some of a very high yield value, although they all measured up to the same viscosity. The result was that when some of the paints were applied to the boards, they would flow and carry the pigment particles down, leaving bare spots. Some paints failed on that account. If all had been run to the real yield value by this apparatus, I think the results would have been different, and I believe Committee D-1 in the future might carry on a line of experiments with that in view. In future specifications, where it is stated that paint shall not flow or slip when applied to vertical surfaces, we could make a more definite statement as to the yield value rather than an indirect statement as to what it should not do.

Mr. Ingalls. MR. F. P. INGALLS.—Mr. Gardner has practically stated what I have in mind. There were some 240 paints in the test to which he refers. In this test it was desired to have all of these paints of correct and identically the same consistencies. The best instrument which we had at that time with which to do this was the Stormer viscosimeter; a torsion type of instrument which was supposed to give better results than a flow type, because most of the paints would not run through a tube of the usual size. The paints were standardized against a glycerin concentration with all the care possible; yet as a matter of fact it is probable that no two of the paints were really of the same consistency, determined by the method described in this paper.

Mr. Ingalls. If there has been one indefinite term in general use in paint technology, it has been the term "body"; something that we all know all about and yet none of us, by any possibility, has ever been able to define. We all seem to know when a paint has a good body, when it is too thin or too thick, but we have never been able to state quantitatively what "body" is. The plastometer described in this paper gives us the first assurance of the possibility of accurately defining this important term, and I believe that the instrument has possibilities that have hardly been more than touched. Important developments are bound to follow the proper and effective use of an instrument of this kind, especially if those interested in the study of paint will take hold of it and apply it to their problems.

Mr. Chapman. MR. CLOYD M. CHAPMAN.—I have listened with considerable interest to the last two speakers, who emphasized the practical need of such an instrument. I wonder if the originator of the instrument would encourage us to think that we might, within a reasonable time, be able to purchase an instrument to work with?

Mr. Bingham. MR. BINGHAM.—I would be very glad to know from the Society whether there is a demand for such an instrument as that, because two or three firms have been talking with me about having it constructed and seem to be willing to put it on the market if there is a demand for it. However, I have not actually closed with any firm in regard to it.

The Chairman. THE CHAIRMAN (MR. G. B. HECKEL).—I should think it may be taken for granted that there would be a demand for such an instrument among paint technologists, but of course the number of paint technologists in the United States is limited.

Mr. Voorhees. MR. S. S. VOORHEES.—Referring to the statement made by Mr. Breyer in regard to the difference in the curves, one starting from the origin and one at some point away from the origin, I should like to ask Mr. Bingham whether, if more time had been given, both curves might have started from the origin, or whether that would be impossible from his experimental data.

Mr. Bingham. MR. BINGHAM.—It seems to me that that question is fairly well settled by the fact that in producing the flow, we have used varying pressures; and with very small pressures, of course, the flow would take a long time, whereas with very high pressures

Mr. Bingham. it would take a comparatively short time. The answer to that question is that when the pressure is comparatively large, those points lie almost exactly on a straight line, as you see in the paper. However, when the pressure is very small, the curve deviates somewhat. Now it has seemed to us that the explanation of that is seepage. It is almost necessarily true that there is seepage when you have a series of small particles which are holding back the flow. The liquid present tends to flow between those particles, and that flow is seepage. There is a viscous flow between the particles, as well as a plastic flow of the material as a whole, and when the pressure is very small, there must be a correction applied. After the corrections are made, we believe that the curve would be absolutely a straight line.

Now answering a question that was raised by an earlier speaker, it seems probable from experiments that have already been made,—although we are anticipating in giving this information,—that in a thin paint the viscosity is not going to be a constant. With a liquid, the viscosity is of course a constant; it does not make any difference what the pressure is, if proper corrections are made. But as soon as you put a single particle into the liquid, you may have introduced a correction for plastic flow; so, with a very viscous liquid which has a *few* of these particles suspended in it, you have probably viscous flow with a correction for plastic flow.

On the other hand, when dealing with a viscous liquid which contains so much larger number of particles that the material is plastic, as for example, a paint, then there is probably a correction for viscous flow, that is, for seepage, whenever the pressure producing the shear is small.

Mr. Job. MR. ROBERT JOB.—I should like to ask whether correction would be made when comparing different pigments, for instance making comparisons of red lead paint, as compared with those of ordinary iron oxide.

Mr. Bingham. MR. BINGHAM.—All I can say in regard to that is that we make very careful corrections for the hydrostatic head and that is the only way I can see in which the weight of the pigment would come into consideration.

Mr. Job. MR. JOB.—The point I had in mind of course was simply that we wanted to insert in a specification one definite figure;

but I presume that the density of the pigment would be taken into consideration to a certain extent. In fixing a figure, for instance, we will say for brown car paint, it would be necessary to compare that figure with other similar paints and not with a red lead paint, or other paint of relatively high density. If we were to use the same figure for red lead paint as for iron oxide paint the results might not be comparable. **Mr. Job.**

THE CHAIRMAN.—That is very interesting from a practical point of view; whether in paints of entirely different compositions, if the yield values should be exactly the same, the results would be comparable when applied to practical paints. **The Chairman.**

MR. GREEN.—I can give you some information on that. If you have a lead paint possessing a certain yield value and a paint made up of pigments of lighter density but with the same yield value, the lead paint will flow easier than the other paint; so with a heavy paint it is necessary to have a higher yield value, if you wish to get the same practical results with it that you would with a lighter paint. That is, the paint manufacturer himself must know what yield value his paint should have in order to give the best results; it cannot be put down as a constant for different paints. **Mr. Green.**

MR. CHAPMAN.—I should like to ask the authors how essential this stirring in the vacuum is in the preparation of the sample. In some laboratories, at least, it involves a complication that it would be rather difficult to overcome. **Mr. Chapman.**

MR. GREEN.—For the practical paint man that will be eliminated entirely. We were more interested in studying this from a scientific point of view and wished to get as accurate measurements as possible, which is the reason we introduced that method. We are now working on a plan whereby the volume of flow can be measured directly and it will not be necessary to know the exact density of the paint. Of course we must have an approximate density, to enable us to determine the hydrostatic head in the container, but this will not require stirring in vacuum. The air in the paint itself does not affect the plasticity in any way, that is, the rate of flow under a given pressure is the same whether the paint has air in it or not. If large amounts of air are intentionally beaten into the paint, however, the case will be different. Under such a condition the yield value is likely to rise. **Mr. Green.**

Mr. Chapman. MR. CHAPMAN.—But plasticity is measured by the volume passing in a given time, and to measure volume accurately it is necessary to exclude the air.

Mr. Green. MR. GREEN.—Under atmospheric pressure, the air in the paint does not occupy an appreciable volume; it is only when you put it under low pressure that the air expands to a larger volume. Besides, bubbles of air included in the paint do not affect the resistance in the flow through the capillary; they pass through as if they did not exist and you never notice any difference caused by them. We have tried running the same paint through with and without vacuum stirring, and could not detect any change in the yield value or mobility that could be attributed to the removal of the air.

Mr. Finn. MR. A. N. FINN.—It seems to me that the discussion has shown a very keen interest by members of this Society in an important paper. I would call attention to the work done, I believe some six or eight years ago, by J. L. R. Morgan[1] on the weight of a falling drop, which seems to be rather an important feature in the paper. Along that line he has pointed out the necessity for absolutely calibrating the capillary tube and the pressures, which affect the shape of the drop obtained. This paper represents important work, but at this time I wish to call attention to that part of the work by Morgan in which he goes into a very great detail with respect to differentiating between the proper kind of a drop under pressure and under ordinary flow, and also as to his tubes.

Mr. Green. MR. GREEN.—We anticipated that very thing and discovered a law which is expressed in the paper as "Weight of drop $=(C \times \text{rate of flow}) + C'$. This change in weight of drop would influence our curve if we did not take it into consideration. We actually weigh the drops and the pressure used; the smaller the rate of flow, the smaller the drop. That is true not only of plastic material, but oils and any liquid.

Mr. Breyer. MR. BREYER.—Many paint men after reading over the description of the plastometer have concluded that the machine is one that can only be used in the scientific or research laboratory for occasional determinations. I have, however, followed the development from the beginning, more from the standpoint of

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[1] *Journal*, Am. Chem. Soc., Vol. 33, pp. 349–62.

Mr. Breyer. its practical application than from the purely scientific viewpoint, and I am convinced that a modification of the machine can be built and used in a manner exactly similar to all the common testing laboratory appliances where relative figures are in general the only ones desired and where the complication of reducing back to absolute units is unnecessary. I believe that in a short while an instrument will be developed on this principle upon which a determination of plasticity can be made as quickly as an ordinary viscosity can be determined upon the common types of viscosimeters.

The Chairman. THE CHAIRMAN.—I think Committee D-1 on Preservative Coatings for Structural Materials will agree that the authors have given the committee something to think about. It is very possible some of the sub-committees will want to introduce this matter into their researches. It will probably come as a surprise to the paint world at large to know that they have apparently been "barking up the wrong tree" for many years in trying to measure the viscosity of a material which, properly speaking, has no viscosity, and which, if it has a viscosity, does not depend upon that property for its value.

A VISCOSIMETER FOR GASOLINE.

By Winslow H. Herschel.

SUMMARY.

The short-tube viscosimeters which are in ordinary use for determining the viscosity of lubricating oils can not be used with gasoline, for which it is necessary to employ an instrument with a much longer outlet tube. The Ubbelohde viscosimeter, primarily designed for kerosenes, appeared suited to the purpose and two instruments of this type were used in determining the relation between time of discharge and viscosity in poises. By a large number of runs with water and ethyl alcohol solutions, liquids of known viscosity, it was found that

$$\text{Kinematic Viscosity} = \frac{\text{Viscosity, in poises}}{\text{Density, g. per cc.}} = 0.0000887\, t - \frac{1.438}{t},$$

where t is the time of discharge in seconds.

It is generally recognized that the specific gravity test is an uncertain guide to the quality of kerosene or gasoline, if taken by itself without information as to the source of the crude oil. This was confirmed by the tests on gasolines, their order when arranged according to densities being quite different than when arranged according to viscosities. A fractional distillation is often used as a substitute or supplement to the specific gravity test, and this gives valuable information. It requires, however, more complicated apparatus and greater skill than are needed to test viscosity.

A VISCOSIMETER FOR GASOLINE.

BY WINSLOW H. HERSCHEL.

THE UBBELOHDE VISCOSIMETER.

The Engler as well as the Saybolt Universal Viscosimeter has an outlet tube only seven diameters in length and with these instruments it is impossible to detect the differences in viscosity of different samples of gasoline. An instrument with a tube 24 diameters in length for illuminating oils was suggested by Engler and constructed by Ubbelohde. Although Lockhart[1] refers to it as the Engler-Ubbelohde viscosimeter, it seems preferable to call it simply the Ubbelohde viscosimeter.

This instrument, which is illustrated in Fig. 1, is similar to the Engler but differs from it in being provided with an overflow pipe to determine the initial level of the liquid. This overflow, however, can not be used with water, and therefore the water rate is determined as follows: Alcohol is poured into the container until it runs out of the overflow. When the flow has ceased, the container is emptied by pulling a skewer out of the top of the outlet tube, and the volume of alcohol held in the container is measured. This same volume must be used in finding the water rate. If a greater volume of water is poured into the container, there is a tendency for it to gather around the overflow and cause an inaccuracy in the head producing flow.

Table I contains the standard dimensions of the Ubbelohde viscosimeter[2] together with the dimensions of two instruments of the Bureau of Standards. Except for d_2 Table I contains the corresponding dimensions as prescribed for the Engler and Saybolt viscosimeters.[3] The average head must be calculated in the same manner as for these instruments, except for the

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[1] L. B. Lockhart, "American Lubricants," p. 214 (1918).

[2] D. Holde, "The Examination of Hydrocarbon Oils," translated by E. Mueller, p. 56 (1915).

[3] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 555 (1917); Vol. XVIII, Part II, p. 364 (1918). *Technologic Paper No. 100*, Bureau of Standards, p. 21 (1917). *Technologic Paper No. 112*, Bureau of Standards, p. 5 (1918).

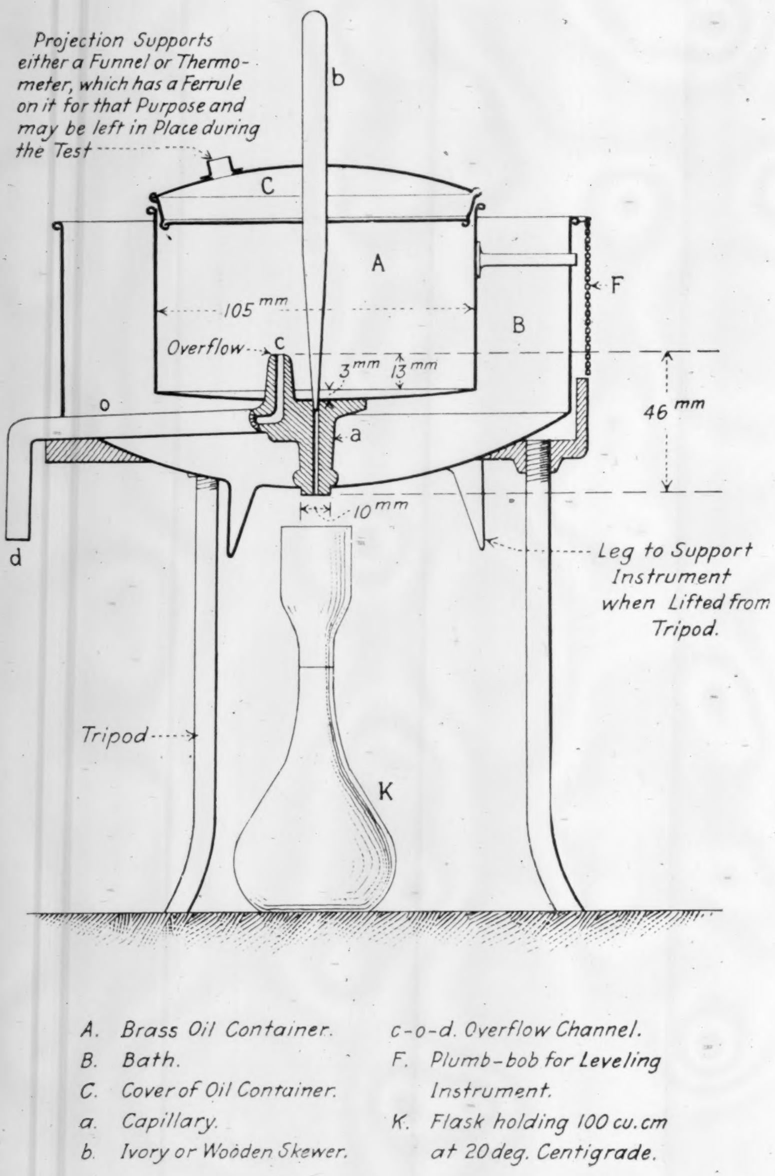
Projection Supports either a Funnel or Thermometer, which has a Ferrule on it for that Purpose and may be left in Place during the Test
b
C
A
F
105 mm
B
Overflow
c
3 mm
13 mm
46 mm
o
a
10 mm
d
Leg to Support Instrument when Lifted from Tripod.
Tripod
K
A. Brass Oil Container.
B. Bath.
C. Cover of Oil Container.
a. Capillary.
b. Ivory or Wooden Skewer.
c-o-d. Overflow Channel.
F. Plumb-bob for Leveling Instrument.
K. Flask holding 100 cu.cm at 20 deg. Centigrade.

FIG. 1.—The Ubbelohde Viscosimeter.

introduction of d_2 in the following equation for the volume discharged:

$$Q = 100 = \frac{\pi}{4} (D^2 - d_2^2) (h_1 - h_2) \ldots\ldots\ldots\ldots \quad (1)$$

in which h_1 and h_2 are the initial and final heads, respectively. The dimension d_1 is of less importance and slight variations in its size would have no effect, since the jet does not spread out over the whole end surface of the outlet tube.

TABLE I.—DIMENSIONS OF UBBELOHDE VISCOSIMETERS.

Dimension.	Normal.	Tolerance.	Bureau of Standards' Instruments.	
			No. 21.	No. 22.
Inner diameter of outlet tube at top, cm.	0.125	±0.001	0.1311	0.1306
Inner diameter of outlet tube at bottom, cm.	0.125	±0.001	0.1282	0.1277
Outside diameter of outlet tube at bottom, d_1, cm.	1.0	±0.05	0.9	0.9
Length of outlet tube, l, cm.	3.0	±0.01	2.934	3.068
Diameter of container, D, cm.	10.5	±0.10	10.579	10.576
Outside diameter of overflow pipe, d_2, cm.	....	....	0.67	0.68
Initial head on bottom of outlet tube, h_1, cm.	4.6	±0.01	4.545	4.702
Average head, h (calculated), cm.	3.992	....	3.950	4.104
Water rate, seconds	200.	±4.0	199.9	198.6
Capacity of container, cc.	....	....	132.	132.

DETERMINATION OF VISCOSITY IN POISES BY THE UBBELOHDE VISCOSIMETER.

It is usual with the Ubbelohde viscosimeter to express viscosities in Ubbelohde degrees obtained by dividing the time of discharge for the oil by the "water rate" or time for 100 cc. of water at 20° C. (68° F.). This purely arbitrary unit should not be confused with the Engler degree, which is another purely arbitrary time ratio. All such difficulties are avoided if viscosities are expressed in poises and it therefore appeared desirable to determine an equation for calculating the viscosity in poises μ, from the time of discharge in seconds t.

It has been shown in previous papers, already referred to, that for an efflux viscosimeter in which the pressure causing the flow is due entirely to the head of the liquid whose viscosity is to be measured,

$$\text{Kinematic Viscosity} = \frac{\text{Viscosity, in poises}}{\text{Density, g. per cc.}} = A\ t - \frac{B}{t} \ldots \quad (2)$$

in which A and B are instrumental constants which may be calculated from the dimensions of the instrument with the help of two corrections, m and λ. The former is the coefficient of the kinetic energy correction; the latter is the "Couette correction" which is made necessary by end effects other than acceleration.

In a convenient graphical method for determining m and λ, described in previous papers,

$$\mu' = \frac{\pi g d^4 \gamma h t}{128 Q l} = \frac{g d^2 \gamma h}{32 v l} \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where v is the mean velocity of flow, d is the average inside diameter of outlet tube, and γ is the density in grams per cubic centimeter. The true viscosity, μ, may be obtained from the formula:

$$\mu = \frac{\pi g d^4 \gamma h t}{128 Q (l+\lambda)} - \frac{Q m \gamma}{8\pi (l+\lambda)} \ldots\ldots\ldots\ldots\ldots \quad (4)$$

under conditions when the effect of m and λ on the value of μ is so slight as to render negligible the error in the values assumed for these corrections. If Reynolds' criterion $\frac{v d \gamma}{\mu}$ is plotted against the ratio $\frac{\mu'}{\mu}$, then

$$m = \frac{32 l}{d \tan \theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$\lambda = l\left(\frac{\mu'}{\mu} - 1\right) \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where θ is the angle between the calibration curve and the axis of abscissas, and $\frac{\mu'}{\mu}$ in Eq. 6 is the value read at the point where the calibration curve, extended, intersects the axis of abscissas.

Tests were made with instruments Nos. 21 and 22 using distilled water, 10, 30 and 50-per-cent ethyl alcohol solutions, and 20 and 40-per-cent sucrose solutions.[1] The results are shown

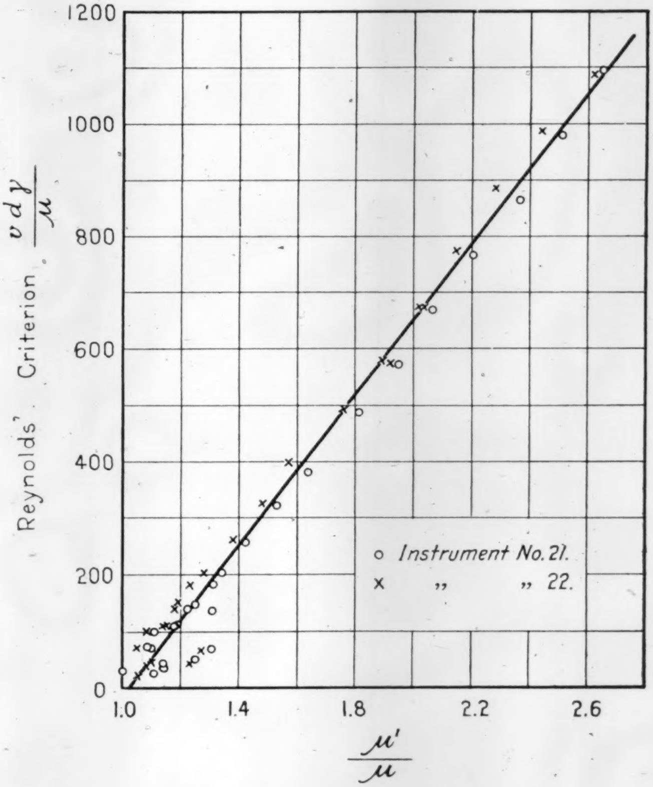

FIG. 2.—Calibration Curve of Ubbelohde Viscosimeter.

in Fig. 2, where it will be noted there is no indication of a bend in the calibration curve. This indicates that the critical velocity is not reached with water in the Ubbelohde viscosimeter and that it may be used as a calibrating liquid. It was found that no effect could be noticed due to difference in surface tension of alcohol and sucrose solutions, so that the high surface tension of pure water is no objection to its use in this instrument.

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[1] Further details in regard to these tests will appear in Technologic Paper No. 125 of the Bureau of Standards.

By substituting in Eq. 4 the average dimensions of instruments Nos. 21 and 22, the following formula for kinematic viscosity was obtained:

$$\frac{\mu}{\gamma}=\frac{0.0002717}{3.001+\lambda}t-\frac{3.979\,m}{(3.001+\lambda)\,t}\quad\ldots\ldots\ldots\ldots\quad(7)$$

and by Eqs. 5 and 6 it was found that $\lambda=.0642$ and $m=1.107$. Substituting these values in Eq. 7,

$$\frac{\mu}{\gamma}=0.0000887\,t-\frac{1.438}{t}\quad\ldots\ldots\ldots\ldots\ldots\quad(8)$$

APPLICATIONS OF EQUATION 8.

As the kinematic viscosity of water at 20° C. is 0.010068, the time of discharge calculated from Eq. 8 is 197.2 seconds. This agrees fairly well with the water rates found experimentally and given in Table I. Care should be taken not to apply Eq. 8 above the critical velocity. If it is assumed that Reynolds' criterion has a value of 1400 at the critical velocity, it may be calculated that t is equal to 155 seconds, and the equation should therefore be used with caution when the time of discharge is less than this value. With long tubes the value of Reynolds' criterion at the critical velocity is generally found to be about 2000. As the lowest value found for short tubes was 800, the value of 1400 was taken as a very rough estimate of the value for this tube, which is 24 diameters in length.

Fig. 3 shows time ratios of the Ubbelohde and Engler viscosimeters according to data given by Lockhart for kerosenes, the tests of Fig. 2, and others previously published. The curve has been drawn as calculated by Eq. 8 and the Engler equations

$$\frac{\mu}{\gamma}=0.00147\,t-\frac{3.74}{t}\quad\ldots\ldots\ldots\ldots\ldots\quad(9)$$

for use when t is 56 seconds or over, and

$$\frac{\mu}{\gamma}=0.000705\,t-\frac{1.33}{t}\quad\ldots\ldots\ldots\ldots\ldots\quad(10)$$

when t is less than 56 seconds and the flow takes place above the critical velocity. Eq. 10 is not recommended for use in viscosimetry, and it was only used for the sake of completeness in Fig. 3. It will be seen that as the time of discharge increases the time ratio increases, and from the values of A in Eqs. 8 and 9 it may be calculated that the time ratio has a constant value of 16.6 when the kinetic energy correction is negligible.

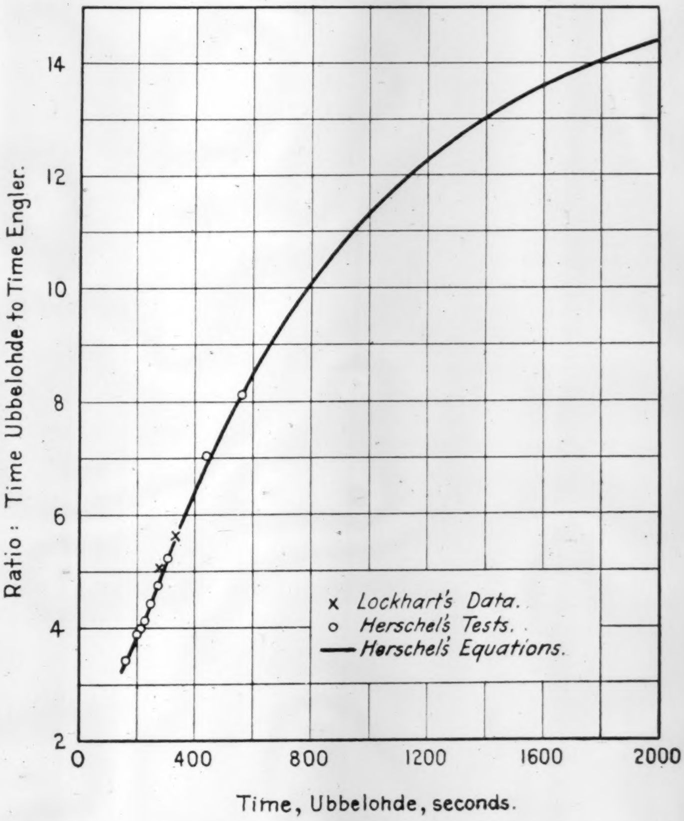

FIG. 3.—Time Ratio, Ubbelohde and Engler Viscosimeters.

THE FLUIDITY OF GASOLINE.

Holde gives data from which the viscosity of various kerosenes may be calculated, but there is very little published information in regard to the viscosity or fluidity of gasoline. With gasolines it is more convenient to consider fluidity, the reciprocal of the viscosity in poises, because the temperature-fluidity curve is more nearly a straight line than is the temperature-viscosity curve and also because decimals are avoided.

Table II shows fluidities of various gasolines as determined by the Ubbelohde viscosimeter and calculated by Eq. 8. They are numbered in the order of their specific gravities. Fluidities calculated from times of discharge less than 155 seconds have been marked and should be accepted with caution.

TABLE II.—FLUIDITIES OF GASOLINES AT VARIOUS TEMPERATURES.

Gasoline No.	Specific Gravity, 15°.6 C. / 15°.6 C.	Fluidities at Given Temperatures, deg. Cent.					
		5	15	25	35	45	55
1	0.757	145	166	193	212	235	262
2	0.748	130	151	170	194	214	243
3	0.743	129	156	185	203	227	...
4	0.726	202	233	264	293	324	360[a]
5	0.722	189	219	244	278	308	342[a]
6	0.717	176	208	239	277	295	...
7	0.716	197	217	256	289	321	341[a]
8	0.708	203	230	257	298	332	360[a]
9	0.702	233	261	296	321	358[a]	400[a]
10	0.701	230	262	287	333	373[a]	398[a]
11	0.699	233	269	306	335	372[a]	423[a]
12	0.694	251	286	316	354[a]	387[a]	427[a]
13	0.680	288	323	365[a]	413[a]	441[a]	475[a]
Kerosene	0.813	39	47	61	71	84	...
Water[b]	.....	66	88	112	138	167	197

[a] Calculated from times of discharge less than 155 seconds, and should be accepted with caution.

[b] E. C. Bingham and R. F. Jackson, *Scientific Paper No. 298*, Bureau of Standards, p. 75 (1917).

The table shows that gasolines are less viscous and kerosenes are more viscous than water.

It will be seen that the order of the gasolines would have been quite different if arranged according to fluidity instead of according to specific gravity. Bingham[1] has shown that the fluidity-vapor pressure curves of the aliphatic hydrocarbons are practically identical. This shows that the vapor pressure may be determined by the fluidity for any of these pure substances and suggests a close connection between fluidity and

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[1] E. C. Bingham, *Journal*, Am. Chem. Soc., Vol. 43, p. 296 (1910).

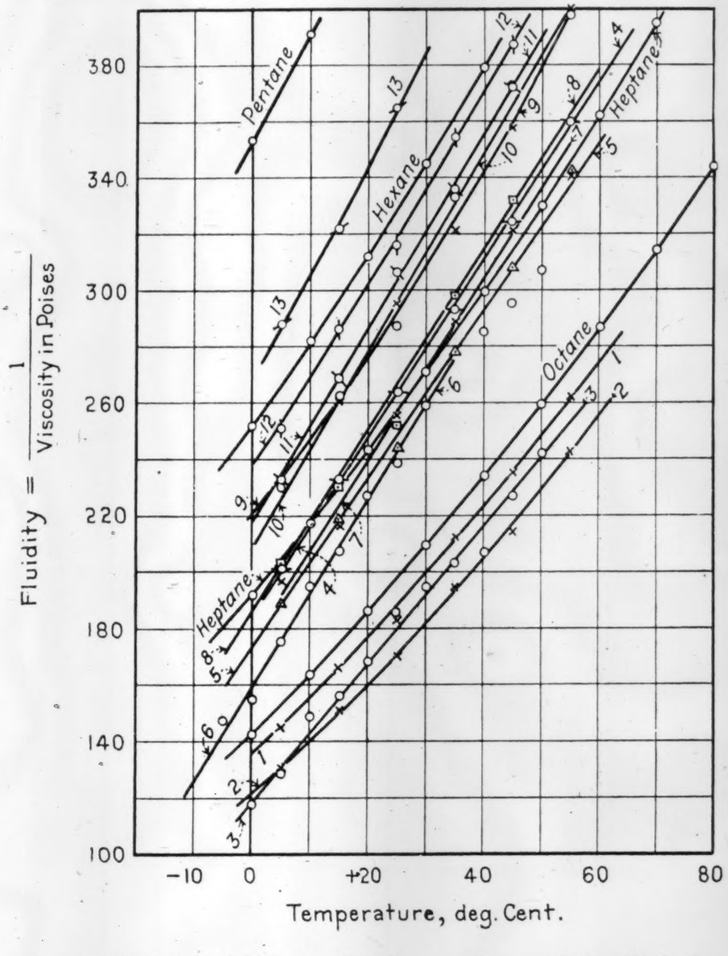

FIG. 4.—Fluidities of Thirteen Gasolines and Four of the Aliphatic Hydrocarbons.

volatility of gasolines which are mainly composed of these hydrocarbons. The exact relation between fluidity and vapor pressure of gasolines could not be determined. The experimental determination of the vapor pressure of gasolines has been found to yield widely discordant results, because the non-homogeneity of the gasolines makes the observed vapor pressure extremely sensitive to slight changes in the experimental conditions.

Fig. 4 was plotted from the data of Table II and from tables of Bingham and Harrison.[1] Ordinary commercial gasoline, of which Nos. 2 and 3 are examples, has about the same fluidity as octane. Most of the aviation gasolines, Nos. 4 and 7 to 12, have a fluidity between those of heptane and hexane. Since the temperature-fluidity relation is determined by a practically straight line, these gasolines could be specified by the fluidity at two temperatures.

CONCLUSION.

The usual method of judging the volatility or suitability of a gasoline by the density is only a rough approximation. Fluidity, which may be easily determined with a suitable viscosimeter, might prove, either alone or in conjunction with other tests, to be a preferable criterion. The Ubbelohde viscosimeter, designed primarily for use with kerosene, serves well enough for a commercial determination of the fluidity of gasoline.

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[1] E. C. Bingham and J. P. Harrison, *Zeitschrift für Physikalische Chemie*, Vol. 66, p. 12 (1909).

STEAM HOSE.

By H. J. Force.

SUMMARY.

Steam hose in train service frequently fails by contracting in length to such an extent that it becomes uncoupled in passing around a short curve. Failures may also be traced to excessive expansion in diameter, which causes the hose to blow off from the coupling.

Hose manufactured from duck with a heavy friction and one or more layers of braiding, as briefly described in the paper, will show no contraction in length nor expansion in diameter under the most severe service conditions.

Tests of a number of samples of four grades of steam hose are given in the paper. These tests include observations on hose steamed to bursting 10 hours a day at 60-lb. pressure.

It is recommended that hose subjected to any considerable temperature should be made of three-ply calendered tubing.

STEAM HOSE.

By H. J. Force.

The object of this paper is to describe briefly a process of manufacture of steam hose which will neither contract nor expand when in service.

When made from duck alone, steam hose has been found to contract to such an extent in service that in some cases it becomes uncoupled when passing around a short curve.

Again, the failure of steam hose in many cases has been traced directly to the excessive expansion which takes place after the hose has been in service for some time. This expansion frequently results in the hose blowing off from the coupling, requiring the use of a special clamp to hold the hose on the coupling.

After making a series of tests, it was decided to build a hose of duck with a heavy friction, and then one or more layers of braiding. If made from duck alone, hose will expand excessively. It is impracticable to make it from braiding alone, but with a combination of duck and braiding a very satisfactory grade of steam hose can be produced which will show no contraction in length and no expansion in diameter under the most severe service conditions.

Table I gives a general description of the process of manufacture of four hose designated as Serials P, Q, R and S.

In Table II are given results of tests to destruction of two samples of steam hose of Serial P. In this hose a special steam-resisting compound was used for the inner tube which was not looked upon favorably by the manufacturer.

In Table III are given the results of tests on ten samples of hose of Serial Q. This hose is similar to that of Serial P except that the regular specification tube was used which had been found to give fairly satisfactory results in service. Aside from this Serials P and Q are of the same composition. The samples of Serial Q, after steaming, withstood a pressure of 60 lb. for about 700 hours, on the average, before bursting.

TABLE I.—DESCRIPTION OF MANUFACTURE OF FOUR KINDS OF STEAM HOSE.

Serial.	Tube.	Thickness, in.	Duck.	Friction.	First Ply of Gum to Anchor Braiding.	First Ply Braiding.	Second Ply of Gum to Anchor Braiding.	Second Ply Braiding.	Outside Cover.
P.....	Special steam resisting hose.	$\frac{1}{8}$	2 ply, not under 23 oz. per sq. yd.	Heavy coated special steam resisting.	$\frac{1}{16}$ in. thick, special steam resisting.	No. $\frac{8}{3}$ yarn in 5 x 5 strands.	$\frac{1}{32}$ in. thick, special steam resisting.	No. $\frac{8}{3}$ yarn in 5 x 5 strands.	$\frac{1}{32}$ in. special steam resisting.
Q.....	Regular specification steam hose.	$\frac{1}{8}$	Same as P.	Heavy coated regular specification steam resisting.	$\frac{1}{16}$ in. thick, regular specification steam resisting.	Same as P.	$\frac{1}{32}$ in. thick, regular specification steam resisting.	Same as P.	$\frac{1}{32}$ in. regular specification steam resisting.
R.....	Regular specification steam hose.	$\frac{5}{32}$				Same as Q			
S.....	Regular specification steam hose.	$\frac{5}{32}$	3 ply, not under 23 oz. per sq. yd.	Special.		Same as Q.	Special.		

TABLE II.—TESTS OF HOSE, SERIAL P.

ALL HOSE STEAMED TO BURSTING 10 HOURS A DAY AT 60 LB. PRESSURE.

Sample No.		1	2
Inside Diameter, in.	Before Steaming	1.625	...
	After "	1.75	1.69
Outside Diameter, in.	Before "	2.625	...
	After "	2.75	2.69
Thickness, in.	Before "	0.125	...
	After "	0.213	0.230
Number of Plies		2	2
Friction, in.	Before Steaming	4.125	...
	After "	3.0	4.0
Stretch of Cover, in.	Before "	7.5	...
	After "	5.0	5.5
Stretch of Tube, in.	Before "	8.5	...
	After "	5.0	5.0
Deflection, in.	Before "	2	2.0
	After "	2.75	1.25
Tensile Strength of Tube, lb. per sq. in.	Before "	600	...
	After "	70	65
Time required to burst under 60 lb., hours	Before "	...	...
	After "	525	840

TABLE III.—TESTS OF HOSE, SERIAL Q.

ALL HOSE STEAMED TO BURSTING 10 HOURS A DAY AT 60-LB. PRESSURE.

Sample No.		1	2	3	4	5	6	7	8	9	10
Inside Diameter, in.	Before Steaming	1.625	......	......	......	......	......	......	......	......	......
	After "	1.72	1.69	1.69	1.69	1.562	1.69	1.69	1.75	1.625	1.75
Outside Diameter, in.	Before "	2.5	......	......	......	......	......	......	......	......	......
	After "	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Thickness, in.	Before "	0.125	......	......	......	......	......	......	......	......	......
	After "	0.113	0.160	0.160	0.167	0.169	0.155	0.160	0.163	0.170	0.171
Friction, in.	Before "	0.25	......	......	......	......	......	......	......	......	......
	After "	1.5	7.0	4.0	1.5	1.25	6.0	8.0	6.0	3.0	4.0
Stretch of Cover, in.	Before "	7.25	......	......	......	......	......	......	......	......	......
	After "	2.5	4.0	3.5	4.0	3.0	3.0	3.0	4.0	3.0	3.5
Stretch of Tube, in.	Before "	7.0	......	......	......	......	......	......	......	......	......
	After "	5.75	3.5	3.0	5.0	6.0	3.0	3.5	4.0	3.5	3.5
Deflection, in.	Before "	3.0	2.75	2.75	2.875	2.875	2.5	2.75	2.5	2.5	2.625
	After "	2.0	2.0	1.75	2.0	1.25	1.25	1.375	2.0	1.75	2.0
Tensile Strength of Tube, lb. per sq. in.	Before "	570	......	......	......	......	......	......	......	......	......
	After "	336	118	125	113	106	111	106	110	111	119
Time required to burst under 60 lb., hours	Before "	615	......	......	......	......	......	......	......	......	......
	After "	60 [a]	555	690	700 [a]	700 [a]	775	785	753	693	693

[a] Test samples removed before bursting.

TABLE IV.—TESTS OF HOSE, SERIAL R.

ALL HOSE STEAMED TO BURSTING 10 HOURS A DAY AT 60-LB. PRESSURE.

Sample No.		1	2	3	4	5	6	7	8	9	10
Inside Diameter, in.	Before Steaming	1.625	......	......	......	......	......	......	......	......	......
	After "	1.72	1.69	1.75	1.812	1.69	1.75	1.625	1.75	1.75	1.75
Outside Diameter, in.	Before "	2.50	......	......	......	......	......	......	......	......	......
	After "	2.53	2.562	2.50	2.562	2.50	2.50	2.562	2.50	2.50	2.50
Thickness, in.	Before "	0.125	......	......	......	......	......	......	......	......	......
	After "	0.134	0.154	0.151	0.153	0.165	0.170	0.180	0.168	0.200	0.175
Friction, in.	Before "	0.625	......	......	......	......	......	......	......	......	......
	After "	0.625	1.75	4.0	7.0	1.875	4.0	6.0	4.0	7.0	7.0
Stretch of Cover, in.	Before "	7.75	......	......	......	......	......	......	......	......	......
	After "	3.5	3.0	4.0	6.0	4.0	4.0	3.0	3.0	4.0	6.0
Stretch of Tube, in.	Before "	5.5	......	......	......	......	......	......	......	......	......
	After "	5.5	4.75	3.50	4.0	5.125	4.0	4.0	4.5	4.0	3.0
Deflection, in.	Before "	2.0	2.625	2.75	2.125	2.75	2.25	3.0	2.75	2.375	2.875
	After "	2.25	1.50	1.50	2.0	2.0	1.25	1.0	2.50	1.50	1.875
Tensile Strength of Tube, lb, per sq. in.	Before "	511	......	......	......	......	......	......	......	......	......
	After "	313	137	130	124	115	106	94	143	90	114
Time required to burst under 60 lb., hours	Before "	700	......	......	......	......	......	......	......	......	......
	After "	60[a]	700[a]	519	530	700[a]	625	754	680	793	525

[a] Test samples removed before bursting.

TABLE V.—TESTS OF HOSE, SERIAL S.

ALL HOSE STEAMED TO BURSTING 10 HOURS A DAY AT 60-LB. PRESSURE.

Sample No.		1	2	3	4	5	6	7	8	9	10
Inside Diameter, in.	Before Steaming	1.625	......	......	......	......	......	......	......	......	......
	After "	1.72	1.562	1.625	1.69	1.75	1.625	1.70	1.562	1.562	1.69
Outside Diameter, in.	Before "	2.625	......	......	......	......	......	......	......	......	......
	After "	2.69	2.625	2.625	2.69	2.625	2.625	2.69	2.69	2.69	2.625
Thickness, in.	Before "	0.125	......	......	......	......	......	......	......	......	......
	After "	0.129	0.160	0.167	0.200	0.200	0.192	0.200	0.195	0.195	0.156
Friction, in.	Before "	1.0	......	......	......	......	......	......	......	......	......
	After "	2.75	6.25	8.0	8.0	7.0	2.0	......	2.5	8.0	3.0
Stretch of Cover, in.	Before "	7.25	......	......	......	......	......	......	......	......	......
	After "	4.0	3.0	6.0	3.5	3.0	5.0	5.0	2.5	3.5	3.0
Stretch of Tube, in.	Before "	5.25	......	......	......	......	......	......	......	......	......
	After "	5.0	4.5	6.0	3.0	4.0	4.0	4.0	4.0	3.5	4.0
Deflection, in.	Before "	2.50	2.0	2.0	2.5	1.75	1.75	2.0	1.625	1.75	1.50
	After "	1.25	1.50	1.0	1.25	0.75	0.875	0.75	0.625	1.0	1.0
Tensile Strength of Tube, lb. per sq. in.	Before "	520	......	......	......	......	......	......	......	......	......
	After "	325	125	132	80	105	94	......	103	177	141
Time required to burst under 60 lb., hours	Before "	700	......	......	......	......	......	......	......	......	......
	After "	60 [a]	700 [a]	700 [a]	1477	770	800	1725	830	1535	862

[a] Test samples removed before bursting.

In the hose of Serial R, the manufacturer endeavored to increase the thickness of the inner tube. Results of tests of this hose are given in Table IV. In some of the lengths of hose tested after steaming, there was an apparent increase in thickness over that of the measured sample, as compared with Serials P and Q, although these too vary considerably showing that the tubes in many cases were undoubtedly not uniform in thickness, at least at various places in the tube. The results of tests on steaming were practically the same as those in Serials P and Q.

In the hose of Serial S the number of plies of duck was increased from two to three, and this apparently had the effect of nearly doubling the life of the hose. It will be noted from Table V that samples Nos. 5 and 6 of this hose burst under 60-lb. pressure, after steaming, in 770 and 800 hours respectively, and that samples Nos. 8 and 10 withstood this pressure about the same number of hours; while samples Nos. 4 and 9 stood up for approximately 1500 hours. A careful investigation of the inner tube revealed the fact that several of these samples were defective. Pieces of wood were found embedded in the inner tube which measured $\frac{1}{4}$ in. wide, $\frac{1}{8}$ in. thick by $\frac{1}{2}$ in. long. The addition of this foreign matter to the rubber compound without a question of doubt caused the failure of samples Nos. 5, 6, 8 and 10, and this is primarily due to the use of machine-made tubes.

It is recommended that in all steam hose or in any hose that is subjected to considerable temperature, a calendered-made tube composed of three distinct layers should be used. This will very materially reduce the chances of dirt or foreign matter getting mixed with the rubber compound, and should a small amount be present the other two calenders will undoubtedly preserve the life of the hose.

This investigation shows:

1. That steam hose should be made of a composition of duck and braid.

2. That machine-made tubes should not be used, and that tubing of three-ply calender should in every case be used in hose to be subjected to any considerable temperature.

3. That a three-calendered tube should be used in hose of all

description, not alone in steam hose, but in air-brake hose, signal hose and any other hose in which any extended service is expected.

4. Special attention should also be given to the fillers in the rubber compound, as many of these when used under certain conditions act as accelerators, producing a decided catalytic effect upon the rubber in the hose in question, with the result that the rubber early becomes oxidized, especially in the case where used in friction. In this case the oxidation of the rubber is so rapid that the friction in steam hose is reduced at a very rapid rate unless extreme care is taken with the kind of fillers which are used in compounds.

It is safe to assume that with the proper method of construction as outlined in this paper, and by using proper grades of rubber and fillers, the life of steam hose can be increased at least 100 per cent.

WIRE TESTING EXTENSOMETER.

By T. D. Lynch and P. H. Brace.

SUMMARY.

This paper discusses the construction, operation, and performance of a simple type of extensometer developed for use in an investigation of the elastic properties of wires and thin strips, such as are used in the manufacture of certain types of springs. This development was undertaken because no commercial instrument could be found which was satisfactory for use where a large number of determinations were to be made.

WIRE TESTING EXTENSOMETER.

BY T. D. LYNCH AND P. H. BRACE.

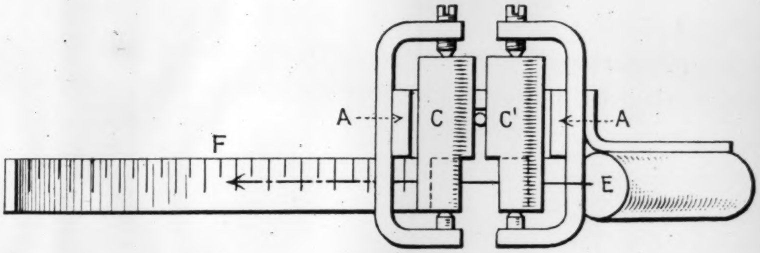
The need for a device for use in obtaining the stress-strain value of metals manufactured in small cross-sections such as wire, ribbon, etc., has long since been apparent. As a result of this need there has been considerable investigation of the problem in the laboratories of the Westinghouse Electric & Manufacturing Co., the result of which has been the design and manufacture of a device on which some very satisfactory commercial results have been obtained.

The following data are presented in the hope that assistance may be rendered to those who are interested in the mechanical properties of wire products, and that more attention may be given to their elastic behavior in making acceptance tests. While in many cases ordinary commercial tests of strength and ductility are satisfactory, it has been found that they do not form a safe guide in selecting material for use where dependence is placed upon elastic properties rather than upon ultimate strength. While ultimate strength and ductility should be considered, an accurate knowledge of the elastic properties of some materials is necessary.

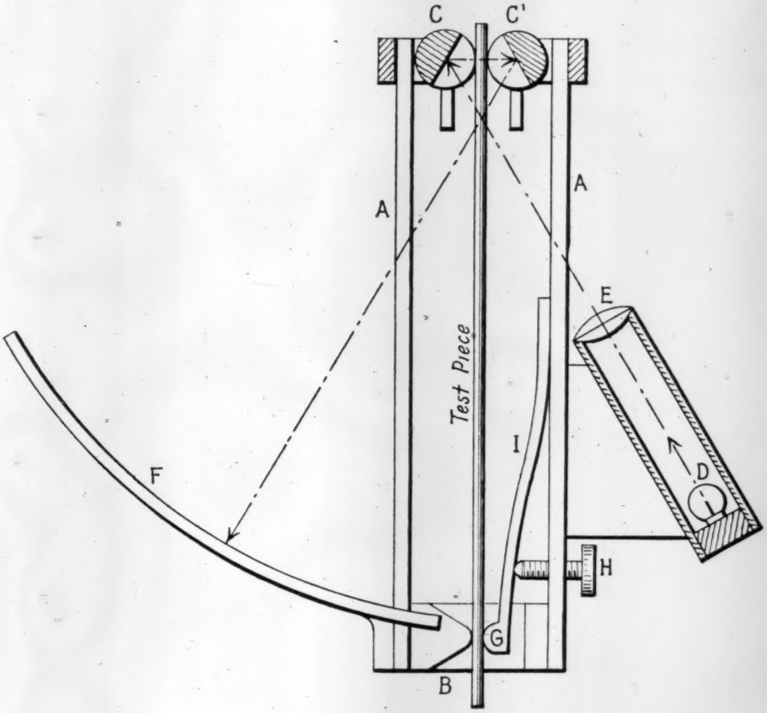
DESCRIPTION.

Referring to Fig. 1, the instrument consists of two flexible steel side pieces, A A, with one end of each securely fastened to a slotted block, B, and having yokes attached to their free ends, carrying small hardened steel rollers, C C', turning on pivot bearings. The axes of the rollers are parallel to each other and at right angles to A A. The line tangent to their contact passes through the center of the slot in the block, B. The rollers are held in firm contact by the elasticity of the side pieces.

A plane mirror is fastened to one end of each roller with its reflecting surface in the roller axis. A short lever is fastened at right angles to the axis of each roller at the opposite end, for use in adjusting its angular position.



End View.


C
C'
A
A
E
Test Piece
I
F
D
H
G
B

Side View.

FIG. 1.—Diagram of Wire Extensometer.

A straight filament galvanometer lamp, *D*, throws a beam of light through the collimating lens, *E*, to the mirror on roller *C*, whence it is reflected to the mirror on roller *C′*, and thence to the curved scale, *F*, where the image of the lamp filament appears as a straight bright line across the scale. Its position is easily read in a normally illuminated room. In the following, this bright line will be referred to as the index of the instrument. The scale, *F*, is curved on the arc of a circle whose center is the axis of the roller *C′*. It is uniformly divided into five hundred parts, and the position of the index is read ordinarily to half a division, and if necessary may be estimated to a fifth of a division. Thus the precision of reading is approximately one part in twenty-five hundred, at full scale.

A specimen under test passes from one jaw of the testing machine, through the slot in the block, *B*, and is securely clamped by a rounded contactor, *G*, carried on a spring, *I*. A thumbscrew, *H*, permits of firm attachment without risk of mechanical injury to the test piece. From *B* the specimen passes between the rollers, *C C′*, which are sprung apart to receive it, to the other jaw of the testing machine. Thus the extensometer as a whole moves with the specimen at *B*, but relatively to it at *C C′*, by an amount equal to the change in length between these points, which will be referred to as the gage points. The rollers are thus turned by an amount depending directly upon the elongation between the gage points, causing a directly proportional movement of the index along the scale.

By reflecting the light from roller to roller as above described, an angular movement is given the emergent beam which is equal to four times that of the rollers. This permits the securing of high magnifications of the elongation of the test specimen without mechanical complications.

Fig. 2 shows the instrument in position and ready for making a test on a wire with a Riehle 5000-lb. hand operated weighing machine.

CALIBRATION.

The scale placed on this instrument was a 50-cm. paper galvanometer scale divided into millimeters. The calibration was accomplished by using a micrometer screw to advance a

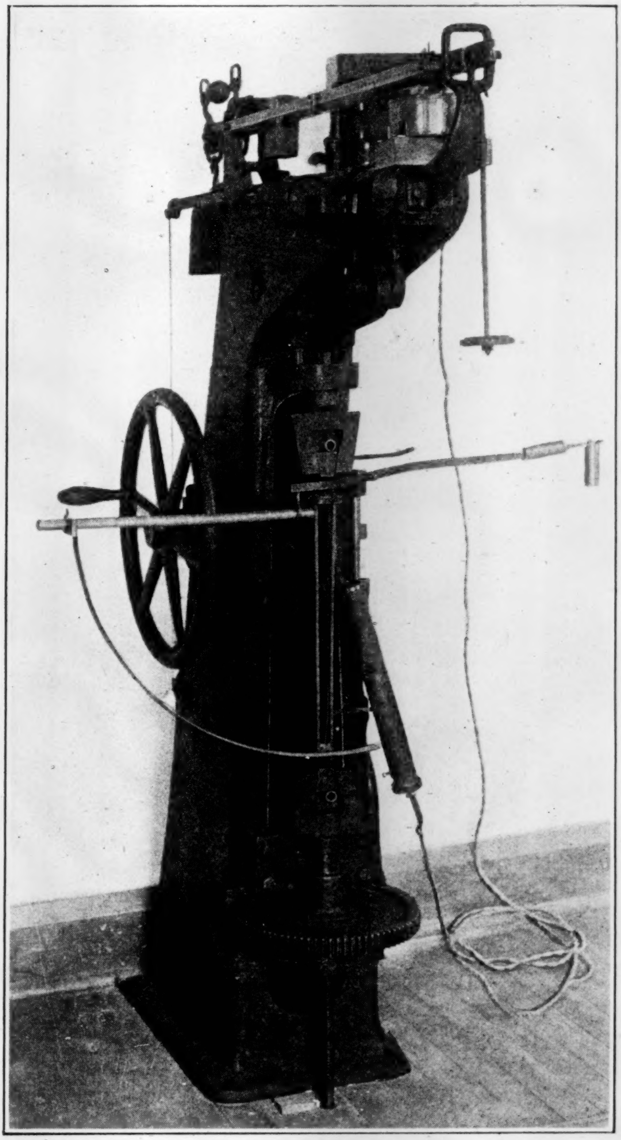


FIG. 2.—Wire Extensometer in Position for Test.

piece of smooth, straight drill rod between the rollers while the extensometer was held rigidly to the same support that carried the micrometer screw. The elongation of a test specimen was thus imitated. The mean of three successive, concordant determinations over a range of 0.04 in. gave an average scale value of 0.0008233 in. per centimeter. Small local deviations from this mean value were found, and from these were constructed the correction curves shown by Fig. 3. From the above scale value it will be seen that by reading to a fifth of the smallest division, length changes as small as 0.00002 in. may easily be detected.

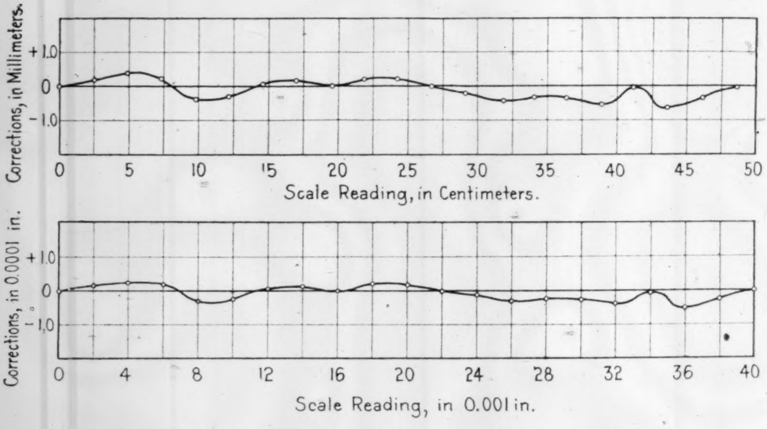


FIG. 3.—Correction Curves Obtained by Calibration.

In order to determine whether or not there was any tendency for the rollers to slip relatively to the specimen, and thus introduce indeterminate errors, quantitative tests were made with the micrometer screw device used in calibration. The drill-rod "test-piece" was moved back and forth so that the index traversed the entire scale. Readings were taken at the top and bottom of the scale at each traverse. Tests over fifteen consecutive cycles showed an accumulated shift of zero of less than 1 mm. on the scale, and a maximum change from one cycle to the next of considerably less. The shift was sometimes positive and sometimes negative. These results show an accuracy of approximately one part in 5000. On two or three occasions peculiar results aroused suspicion that "the rollers were slipping," but repetition of the above test always led to the conclusion that the length changes of the specimen were being faithfully indicated. The question of slip in such cases as the determination of elastic limit by means of the observation of the first permanent set under repeated stresses of increasing magnitude becomes particularly important. Here the requirement is that the zero shall be constant to within a small percentage of the total deflection in order that the first appearance of permanent set shall be correctly observed. The results of our experience indicate that this condition is fulfilled with the present device if handled with reasonable care.

OPERATION.

In use, the extensometer was carried on a counterweighted arm free to move about both a horizontal and a vertical axis. In this way the weight of the instrument was entirely removed from the test specimen so that no great amount of pressure was necessary at the clamping block, *B*, to insure absence of slip. Thus suspended, the instrument was regularly left in place until the specimen failed and data for the entire stress-strain diagram obtained.

In making a test, the specimen was placed in the testing machine and straightened by the application of a small unit load. The extensometer, on its counterweighted arm, was then swung into position; the block *B* slipped over the wire; the rollers sprung apart to admit the specimen and then released when it was in place; and the clamp at *B* tightened; following which the index was brought to zero by means of the levers attached to the rollers. The loading of the specimen then proceeded, scale readings and load readings being taken at suitable intervals to furnish data for the construction of the stress-strain diagram.

When the elongation exceeded 0.04 in., which was the range of the instrument, the index was simply reset to some convenient point on the scale while the load was held constant, and readings taken as before as the load was again increased.

It will be noticed that the length of specimen under test increases with increasing load, while the distance between gage points remains fixed. The effect is to cause a very slight error in the slope of the stress-strain curve, which appears too steep by an amount proportional to the elongation of the specimen. The authors know of no material with which this error would amount to as much as 0.6 per cent at its elastic limit. This error is perfectly definite and may be easily corrected if extreme precision is required. By suitably curving the rollers or scale, or by suitable calibration, the instrument may be made direct reading in terms of elongation of the original length of the test specimen, and corrections made unnecessary.

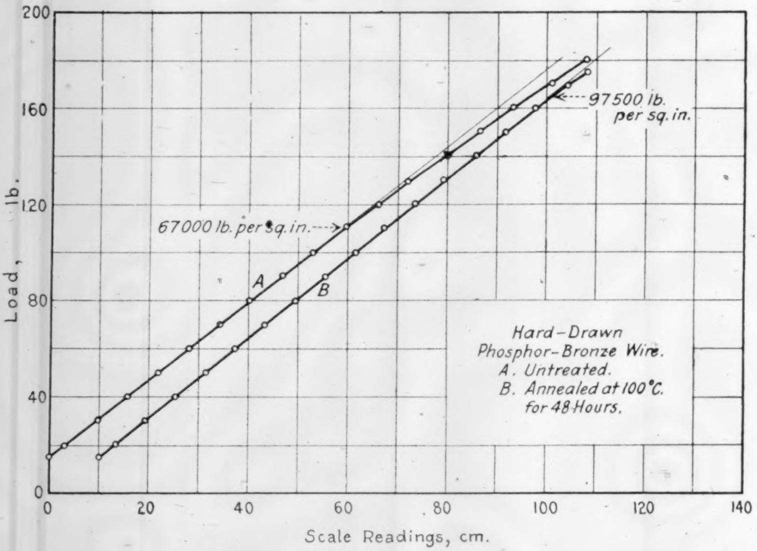


FIG. 4.—Results of Tests on Hard-Drawn Phosphor-Bronze Wire.

PERFORMANCE.

The following data are appended to give an idea of the performance, under actual service conditions, of the extensometer just described.

Fig. 4 shows the results of tests on samples of hard-drawn phosphor-bronze wire. Both samples were from adjacent sections of the same piece. They had been reduced from rod $\frac{3}{16}$ in. square to 46-mil wire without annealing. Thus it will be seen that the samples had been severely cold-worked, and doubtless contained large internal stresses. Sample A was tested as it came from the reel, while sample B was first annealed for 48 hours at 100° C.

The effect of the internal stresses becomes evident when the results of the two tests are compared, and note taken of the indefiniteness of the elastic limit of sample A; its somewhat lower modulus of elasticity is indicated by the greater slope of the straight portion of the curve for B. This effect has been noted in a large number of instances, often to a much greater degree than in the case just cited. By simple stretching of a hard-drawn wire to a point considerably beyond its elastic limit, internal stresses are largely removed. Curves taken before and after stretching, and without intermediate annealing, compare much as A and B above.

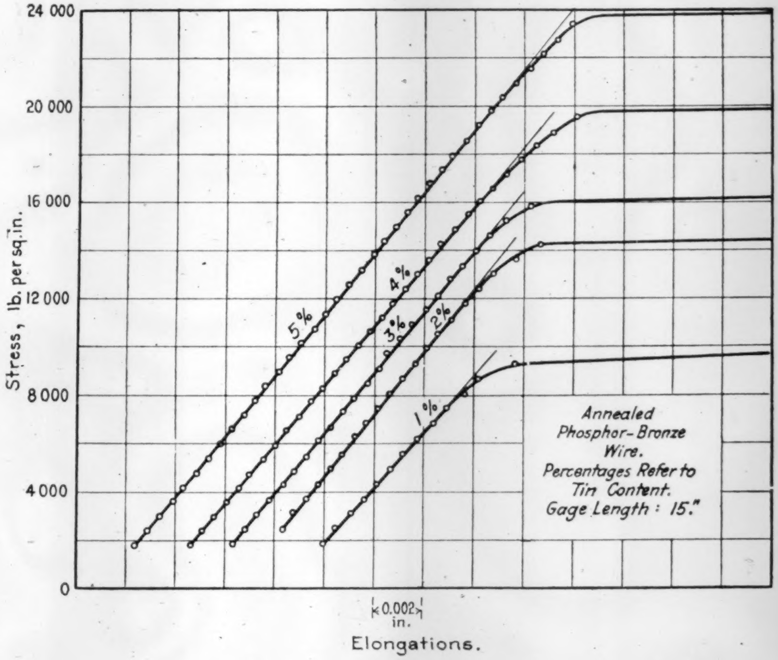


FIG. 5.—Results of Tests on Annealed Phosphor-Bronze Wire Containing Different Amounts of Tin.

Fig. 5 shows the stress-strain diagrams of a series of phosphor-bronze wires containing different amounts of tin, but otherwise similar in composition, and uniformly treated. All were electrically annealed at a temperature of 700° C. for one minute, and allowed to cool under a slight tension in order that they might be perfectly straight when placed in the testing machine. Great care was taken in handling these samples in order not to bend or twist them beyond their elastic limit.

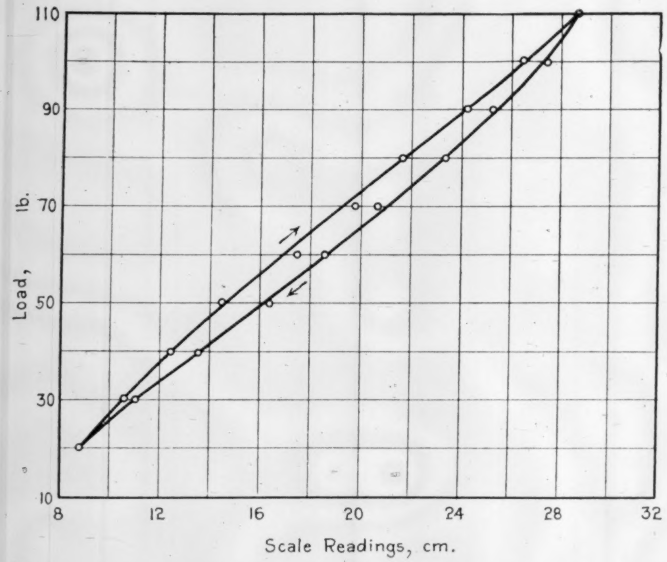


FIG. 6.—Hysteresis Loop for Annealed 0.9 per cent Carbon-Steel Rod $\frac{1}{16}$ in. in Diameter. Theoretical stress-strain curve plotted to scale indicated; deviation from this theoretical curve (indicative of mechanical hysteresis) plotted to scale of abscissas 4 times as large.

It will be seen that although the strength of the alloy increased steadily with the tin content, the modulus of elasticity is not greatly changed.

It is well known that cyclic deformation of an elastic material is accompanied by the absorption of a certain amount of energy. In other words, there is a mechanical hysteresis analogous to the more familiar magnetic hysteresis. This effect is small in the case of deformations within the elastic limit, but is easily measurable with equipment of sufficient precision. An example of this effect in annealed carbon steel is shown in Fig. 6. The manner of plotting the diagram requires some explanation. If the material were perfectly elastic the stress-strain diagram would be a straight line joining the extreme points. In actual materials deviations from this straight line occur as a result of the mechanical hysteresis. These deviations are small, so that for the sake of clearness, the diagram has been constructed by drawing the theoretical stress-strain curve to a convenient scale, as shown by the numbering of the coordinates, and then plotting the deviations from this theoretical curve to a scale four times as large. In this way the course of the hysteresis loop is made more apparent.

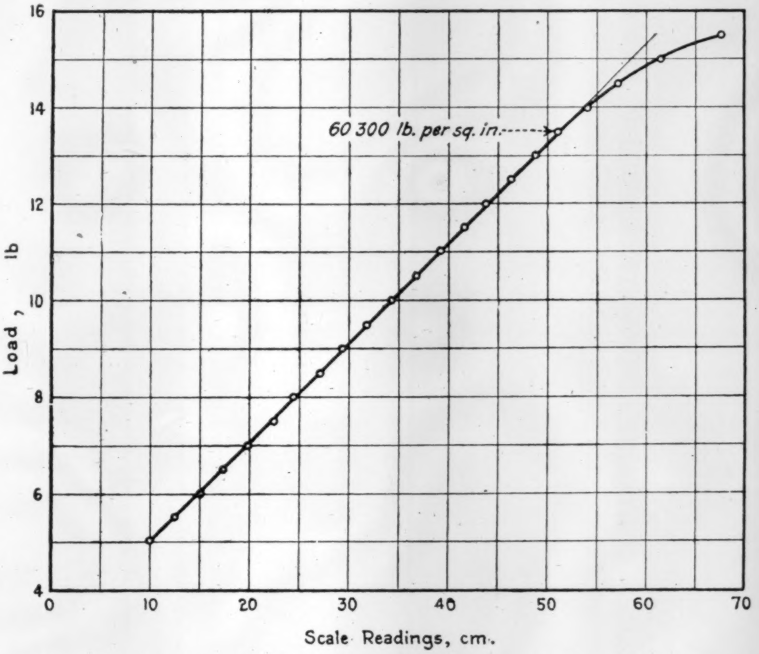


FIG. 7.—Results of Test on Hard-Rolled Thin Silicon-Bronze Ribbon 0.0023 by 0.0975 in. in Cross-Section.

The curve shown in Fig. 7 shows the data secured in the course of a test on some thin hard-rolled silicon-bronze ribbon. The area of this section was only 0.000224 sq. in. The applicability of the instrument to very small sections is well illustrated by these results.

These few examples will illustrate some of the uses to which this extensometer has been put. Other applications will suggest themselves to those interested.

CONCLUSION.

It should be said that the particular instrument here described was experimental and no great refinement in construction was attempted. It has proven so satisfactory over a considerable period in the hands of several different persons, that a second model is being designed with the end in view of securing a lighter instrument of higher precision. Means for varying the distance between gage points will be provided, because in some cases it is desirable to work with shorter specimens than were used here. Improvements will be made in the optical system, and the scale will be direct reading.

The authors are indebted to Dr. P. G. Nutting of this laboratory for valuable suggestions relating to design of the instrument and to Mr. M. J. Williams for able assistance in the collection and reduction of data.

DISCUSSION.

MR. T. D. LYNCH.—I should like to say, in emphasizing one or two points in connection with this paper, that the reason for developing the extensometer described was the necessity of determining the true elastic limit of small wire. We could not determine it with the Ewing extensometer or any other instrument already known and on the market. The point is illustrated by curves A and B in Fig. 4, showing the results of tests on phosphor-bronze wire. Curve A shows an elastic limit of 76,000 lb. per sq. in. for the wire as it came from the draw bench. When the wire had been treated by heating to 100° C. for a short time, the elastic limit was increased to 97,000 lb. per sq. in. as shown in Curve B. The value of 76,000 lb. is not the true elastic limit of the material, but a combination of the elastic limit with the internal stresses present. These internal stresses are removed by heating to 100° C., and this treatment thus enables us to determine the true elastic limit of the material as such. **Mr. Lynch.**

Phosphor-bronze wire frequently becomes brittle in storage when in coils or after it has been made into springs. I have with me two samples of wire taken from very brittle stock, representing one of the cases of hard drawing up to the point where the internal stresses are such that but little additional stress is required to rupture the material. One end of this wire is in the original condition after drawing; the other has been drawn back at a temperature of 100° C. You will note that the untreated end breaks off with only a slight bend, simply snapping off in my fingers, while the treated end, where the internal stresses have been removed, can be bent round and tied into a knot.

I might also add that when springs have been made from the brittle untreated phosphor-bronze they usually break in service, whereas if they have been given this low drawing treatment they do not break in service but last practically indefinitely under the usual stresses.

The Chairman. THE CHAIRMAN (MR. H. F. MOORE).—The chair begs leave to call attention to one feature in the paper. Messrs. Lynch and Brace have apparently developed a form of optical extensometer which may be handled with considerable facility. Those of us who have had to do with the mirror type of instrument have found that it is a very slow and awkward instrument to handle, but this instrument gives promise of combining the extreme delicacy of the "optical lever" with a good degree of facility in use.

FATIGUE TESTING MACHINE.

By F. M. Farmer.

SUMMARY.

The machine described was developed for the Research Sub-Committee of the Welding Committee of the Emergency Fleet Corporation. It was primarily designed to make repeated reversed-stress tests of specimens cut from samples of electrically welded joints in ship plates, but since the machine is so comparatively inexpensive and simple in construction, it is believed a description in the records of this Society may be of value to others interested in the subject of fatigue tests of materials in general.

The conditions which governed the selection of the type of test to be adopted are discussed. The principle of the machine finally constructed is not new but has been applied to fatigue testing by other investigators. It is that of a four-point rotating beam with two "free" supports at the ends and two loads at the middle. This gives a uniform moment throughout that portion of the specimen between the points of application of the loads, a very desirable condition to have in that portion of the welded test specimen in which the joint is located.

A description of the machine is given together with a working drawing and a photograph. The machine occupies a space 5 by 19¼ in. exclusive of the small driving motor. The form of test specimen prepared from samples of welds and from original metal is indicated. The reasons for selecting 25,000 lb. per sq. in. as the standard maximum fiber stress at which all tests are made are discussed.

FATIGUE TESTING MACHINE.

By F. M. Farmer.

The apparatus described in this paper was developed at the Electrical Testing Laboratories for the Research Sub-Committee of the Welding Committee of the Emergency Fleet Corporation. The purpose was to obtain information in regard to the relative durability of electrically welded joints in $\frac{1}{2}$-in. ship plates when subjected to repeated reversed stresses. The principle employed is not new and has been used by other investigators[1] for fatigue tests, but since the machine developed for this particular work is suitable for general fatigue testing and is so relatively simple and inexpensive, it is believed a description in the records of this Society will be of interest and perhaps of value to others who may be interested in this particular phase of materials testing.

Conditions Governing Design of Machine.

A specimen cut from a welded joint in a ship plate (Fig. 1) is not homogeneous but consists of two pieces of plate joined together with metal of decidedly different chemical, metallurgical and physical characteristics. Furthermore, the area of a cross-section through the deposited metal at right angles to the length of the specimen varies throughout the joint because of the "V" shape of the deposited metal and the irregularity of the line of union between the deposited metal and the original metal. Therefore it is essential that the apparatus be of a type which will produce a uniform stress throughout that part of the specimen in which the joint is located.

Another requirement was low cost. It is well known that if reasonably reliable data of this character are desired, a number of specimens of each sample must be tested. Since a large amount of research work was contemplated, this meant the development of a machine sufficiently simple and inexpensive to make it practicable to have a number available so that results could be obtained quickly.

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[1] James E. Howard, "Notes on the Endurance of Steels under Repeated Alternate Stresses," *Proceedings*, Am. Soc. Test. Mats., Vol. VII, p. 252 (1907).

PRINCIPLE OF MACHINE.

The principle employed is that of a four-point rotating beam with two free supports at the ends and two loads at the middle. Fig. 2 shows the familiar shear and moment diagrams for a beam so loaded, in which $W_1=W_2=W_3=W_4=W$ and $x_1=x_2=x$. The moment between a and b is uniform and has the maximum value of Wx. If the beam has a uniform circular section, the maximum fiber stress in all sections between a and b is

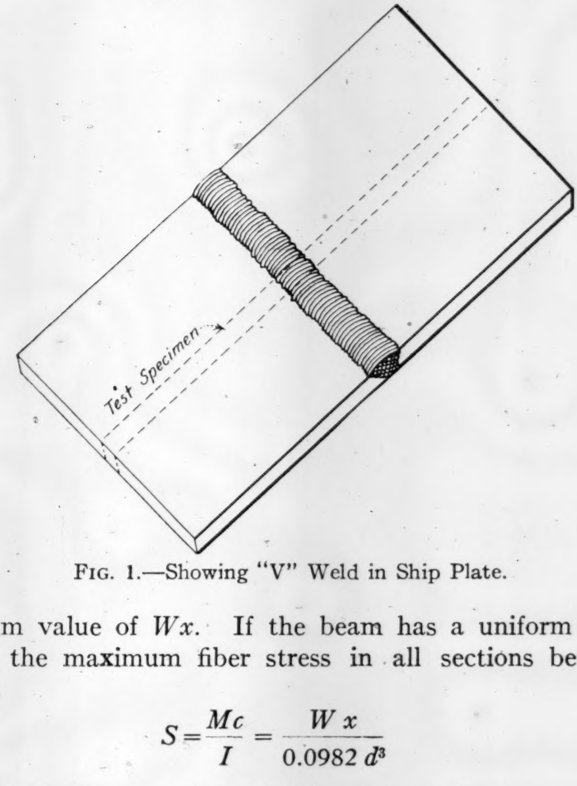

FIG. 1.—Showing "V" Weld in Ship Plate.

$$S=\frac{Mc}{I}=\frac{W\,x}{0.0982\,d^3}$$

in which S = stress in outer fiber in pounds per square inch, M = bending moment in inch-pounds, c = distance from neutral axis to outer fiber, in inches, $= d/2$, I = moment of inertia, W = load in pounds, x = distance between loads and supports, in inches, and d = diameter of beam in inches.

The beam is in tension on the lower side and in compression on the upper side. Thus if a circular rod is turned from a specimen cut from a weld, loaded in the manner indicated above with the joint in the middle and then rotated, the joint will be subjected to a maximum stress equal to S alternately in tension and compression once per revolution.

DESCRIPTION OF MACHINE.

Fig. 3 is a photograph of the machine and Fig. 4 (Plate I) is a reproduction of a scale drawing. The specimen is carried by four self-aligning ball bearings, *a*, *b*, *c* and *d*. The two end ones rest in the pillow blocks, *e* and *f*, the whole being supported on a cast-iron base 5 in. by 19¼ in. One of the pillow blocks provides for longitudinal movement of the bearing due to the slight bending of the specimen. The two equal loads are hung from hooks attached to collars which encircle the outer races of the two middle bearings.

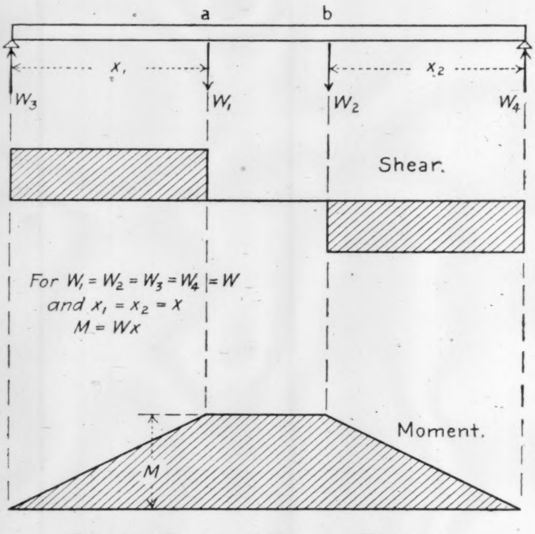

FIG. 2.—Shear and Moment Diagrams.

The bearings are securely fastened at the proper position by means of two split collets of carburized steel with opposite

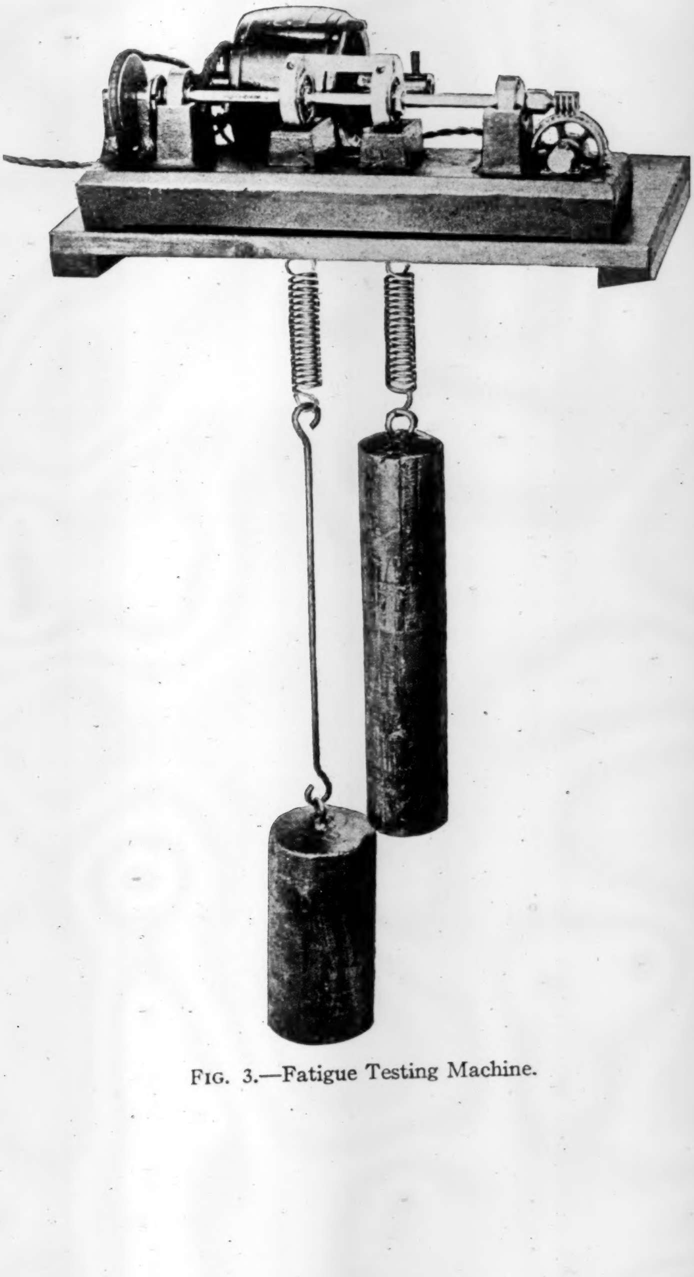

FIG. 3.—Fatigue Testing Machine.

tapers, one entering from each side of the bearing. This produces a wedge action which gives a uniform pressure over the entire bearing surface on the shaft and insures the validity of the assumption that the point of application of the loading forces is at the center of the bearings. The inner collet is counterbored as shown so that the bearing surface on the specimen is as short as possible. The collets are wedged together by a nut on a thread on the inner collet and are loosened with the aid of a wedge key driven under the head of the inner collet.

The specimen is rotated through the loose coupling at one end of the specimen and the revolutions are counted by a suitable counter geared to a worm on the other end of the specimen. These various fittings are most conveniently put in position on the specimen at a vise on a bench. The specimen with the fittings in position is then dropped in position in the machine, the weights hung on to the hooks (with spiral springs intervening) and it is ready to be rotated. The blocks *g* and *h* are merely for the purpose of preventing the weights dropping too far when the specimen fails.

When failure occurs, the specimen will stop rotating because it "binds" and the belt will either slip or be thrown off. However, the preferable way for securing automatic stopping is to provide a simple switch arrangement which will be operated by one of the weights when it drops. This will cut off the motor.

SPECIMENS.

Weld Specimens.—This particular machine was designed for specimens from welds of $\frac{1}{2}$-in. plates, but obviously a machine could be constructed for specimens of any ordinary diameter. It is planned to construct one with a longer base for specimens from $\frac{5}{8}$-in. to 1-in. plate by providing bushings of suitable sizes and arranging for changing the distance between the supporting pillow blocks so that the weight can be kept within reasonable limits.

The standard specimen for the machine described is 13 in. long and 0.4 in. in diameter throughout its entire length. This diameter is about the maximum that can be turned out of $\frac{1}{2}$-in. material which is rarely perfectly straight. Care is taken

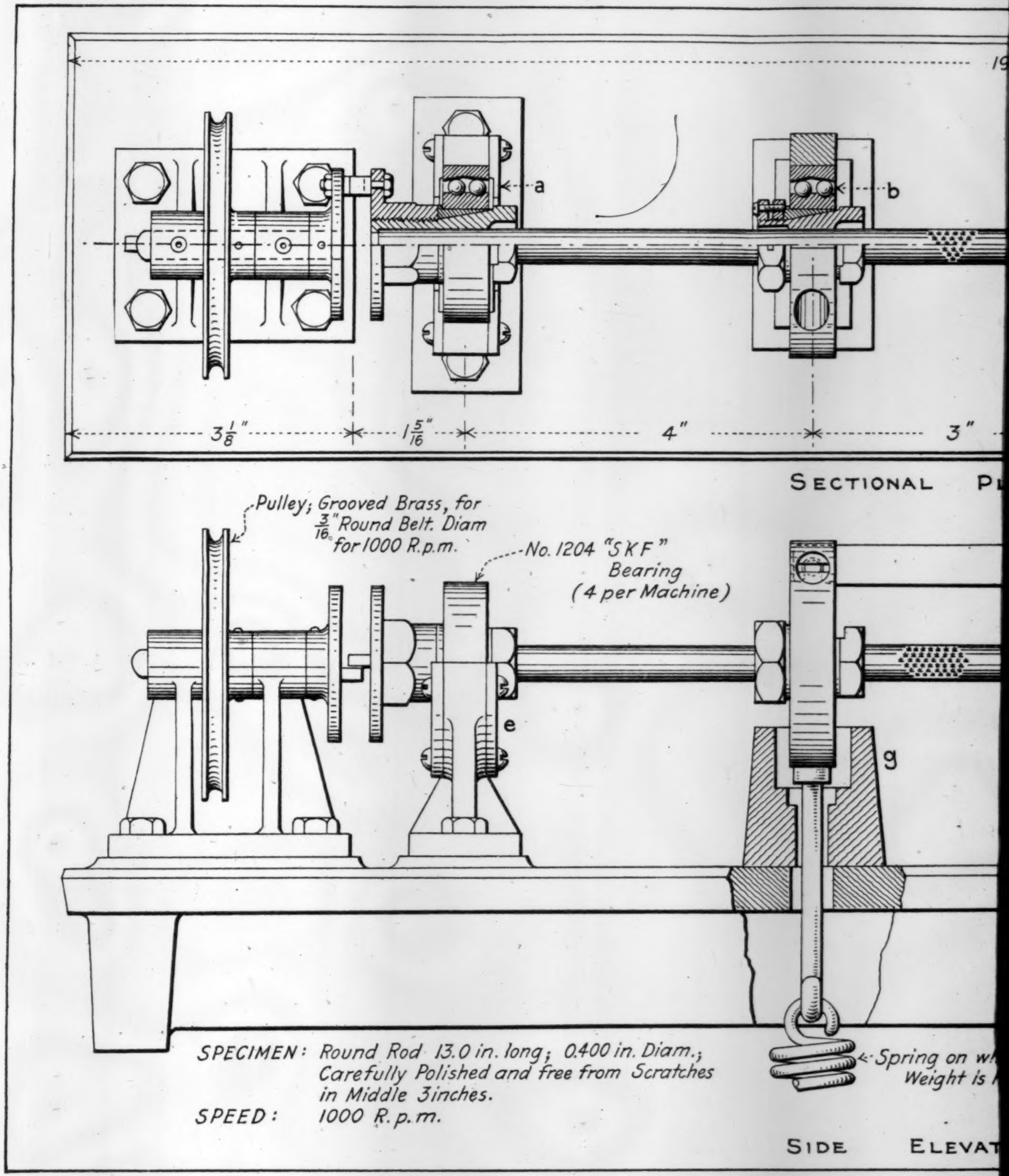
19
a
b
3 1/8"
1 5/16"
4"
3"
SECTIONAL P
Pulley; Grooved Brass, for 3/16" Round Belt. Diam for 1000 R.p.m.
No. 1204 "SKF" Bearing (4 per Machine)
e
g
SPECIMEN: Round Rod 13.0 in. long; 0.400 in. Diam.; Carefully Polished and free from Scratches in Middle 3 inches.
SPEED: 1000 R.p.m.
Spring on wh
Weight is
SIDE ELEVAT

Fig. 4.—Reproduction of Scale Draw

PLATE I.
PROC. AM. SOC. TEST. MATS.
VOL. XIX, PART II.
FARMER ON FATIGUE TESTING MACHINE.

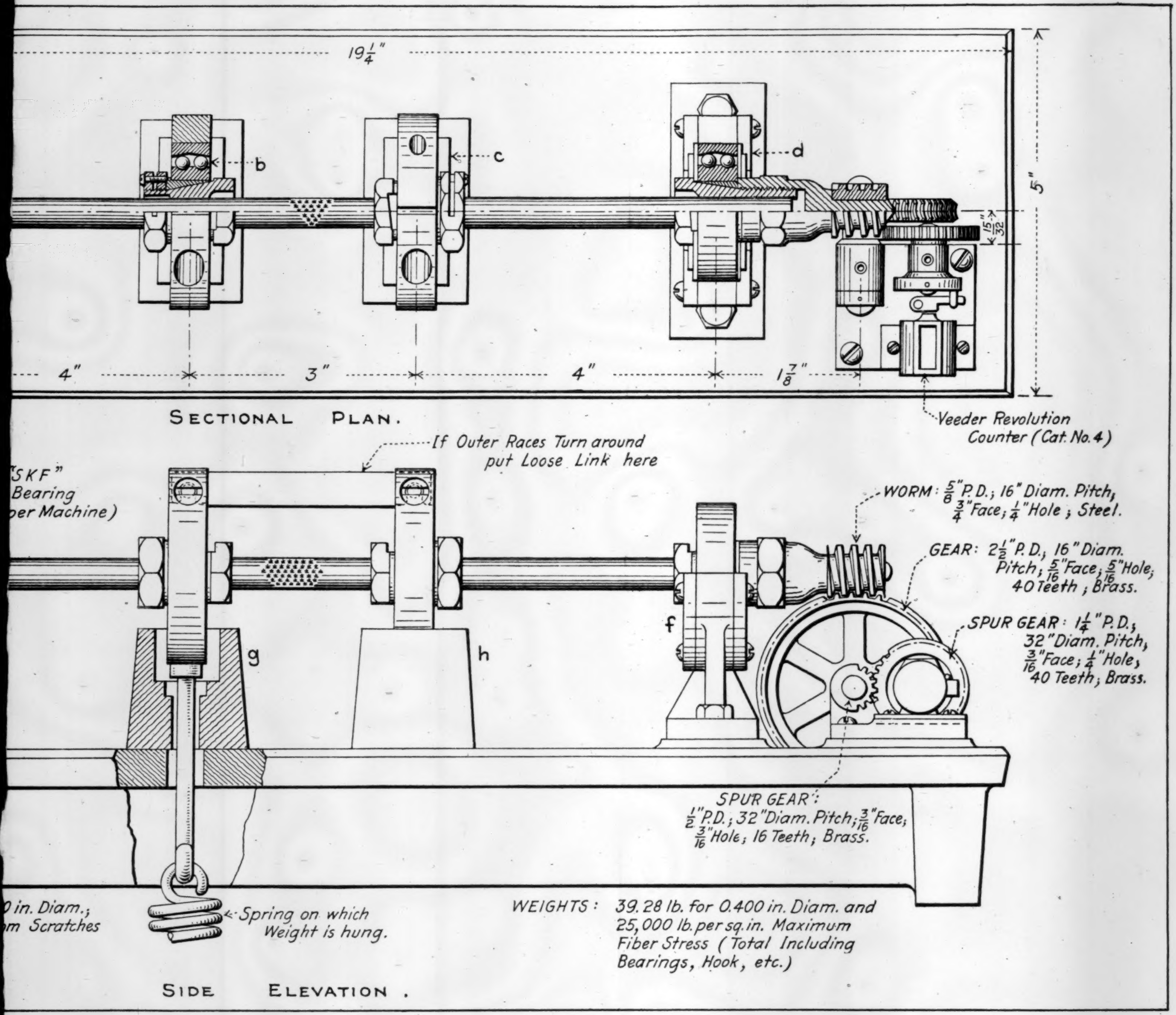
19¼"
5"
b
c
d
15/32"
4"
3"
4"
1⅞"
SECTIONAL PLAN.
Veeder Revolution Counter (Cat. No. 4)
If Outer Races Turn around put Loose Link here
"SKF"
Bearing
per Machine)
WORM: ⅝" P.D.; 16" Diam. Pitch; ¾" Face; ¼" Hole; Steel.
GEAR: 2½" P.D.; 16" Diam. Pitch; 5/16" Face; 5/16" Hole; 40 Teeth; Brass.
SPUR GEAR: 1¼" P.D.; 32" Diam. Pitch; 3/16" Face; ¼" Hole; 40 Teeth; Brass.
f
g
h
SPUR GEAR: ½" P.D.; 32" Diam. Pitch; 3/16" Face; 3/16" Hole; 16 Teeth; Brass.
0 in. Diam.;
m Scratches
Spring on which Weight is hung.
WEIGHTS: 39.28 lb. for 0.400 in. Diam. and 25,000 lb. per sq. in. Maximum Fiber Stress (Total Including Bearings, Hook, etc.)
SIDE ELEVATION.

FIG. 4.—Reproduction of Scale Drawing of Fatigue Testing Machine.

that the diameter in the middle portion is exact and that this part of the specimen is carefully finished free from tool marks or scratches.

Original-metal Specimens.—The criterion of the performance of a joint of any kind is the performance of a similar specimen of the original metal without a joint. Consequently fatigue tests of welds in ½-in. plate should be compared with tests made with the same apparatus and at the same stress on specimens from the original plate. When such tests were made with specimens of constant diameter throughout their length, failure always occurred at one of the load bearings and not between them, as is the case with weld specimens where the joint is (at least at the present stage of the electric fusion welding art) the weakest part of the specimen. It is believed that this is due to the sudden change in the stress distribution (see Fig. 2) at these points and probably also to the radial compressive stress induced at these points by the loads. By reducing the diameter between these points and using long fillets, failure will occur in the central portion of the specimen and the true endurance value of the metal will be obtained.

STANDARD STRESS ADOPTED.

A standard maximum fiber stress of 25,000 lb. per sq. in. is being employed in the testing of weld specimens and the corresponding specimens of original metal. The selection of this value was based on the following considerations: The characteristic which it is desired to test is the elastic property under reversed stress conditions and not ductility, since in practice a material is never intentionally stressed above the elastic limit. This means, therefore, that the stress should be below the elastic limit because, as Prof. H. F. Moore has pointed out, the relative performance of materials in a fatigue test will probably be very different above the elastic limit where the property involved is ductility, than it will be below the elastic limit where the elasticity is the property involved. On the other hand, the higher the stresses, the more quickly results will be obtained. As there is no reason to suppose that the *relative* behavior of different materials will not be the same at low stresses as at high stresses (provided they are below the elastic limit), a stress of

25,000 lb. was adopted. This is as close to the elastic limit of ship-plate steel as it was thought advisable to go.

CONCLUSIONS.

A considerable number of specimens of both welded joints and solid plate have been tested with the first machine built, and it has proved entirely satisfactory. Several more machines will be in service before this paper is presented so that further experience will have been obtained. The general order of the results so far obtained at 25,000 lb. per sq. in. maximum fiber stress is about 500,000 revolutions for specimens with welded joints and about ten million revolutions for specimens without joints, or a proportion of 1 to 20.

It is believed that the advantage which this principle has of making the stress uniform over a finite length of the specimen is an important one. Not only can the exact area at the point of maximum stress be accurately measured, and the stress accurately determined, but this principle can be utilized in a machine which is simple, compact and relatively inexpensive.

The objection may be raised that, so far as testing welded joints is concerned, the specimen is so small that it contains only a small portion of a joint and consequently in order to get reliable knowledge of a joint, a number of specimens along the joint must be tested. In other words, to get reliable fatigue results, the machine should be such that it would take a comparatively wide specimen. But the very fact that a small specimen requires a number of tests to be made is an advantage, because definite knowledge of the uniformity of the strength (or lack of it) along a long weld is very important, and obviously this would not be obtained with a wide sample. Furthermore, with the much greater speed permissible with a small machine and the larger number of machines which could be available, the equivalent in small specimens can be tested just as quickly as the one large specimen.

In closing, the author desires to acknowledge his obligations to Prof. H. L. Whittemore of the Bureau of Standards, who made many valuable suggestions in the course of the development of this apparatus.

DISCUSSION

Mr. Templin. MR. R. L. TEMPLIN.—I should like to ask Mr. Whittemore[1] if he finds in connection with this machine that the coil springs give as good results as the weights.

Mr. Whittemore. MR. H. L. WHITTEMORE.—The dash pot has been used on some machines of this type. I do not know that any difference is found if the results obtained by the use of springs and dash pots are compared. The selection of springs is entirely an economic matter; it is desirable to get a design which is low in cost and easily handled. I think the result obtained shows that the use of springs is satisfactory.

The Chairman. THE CHAIRMAN (MR. H. F. MOORE).—The chair begs leave to call attention to one point raised by Mr. Whittemore and also raised in the discussion of a fatigue paper yesterday.[2] The relative length of endurance of two specimens was spoken of as a measure of the fatigue strength of the specimen; if the relative strength of two fatigue tests is judged by the *stress* which will produce failure at a given number of repetitions the comparison is usually much less striking than when *length of endurance* is used as a measure. If one fatigue test gives an endurance a hundred times as long as another, and then the same two tests are compared upon a basis of stress, the relative value will not be one hundred times, but, perhaps, two or three times. If we judge two fatigue test specimens on the basis of lengths of endurance, we may say that one has an advantage of 300 per cent, whereas if we judge them upon the basis of stress, we may say that one has an advantage of 10 or 25 per cent, a widely different figure. A slight change in stress produces a very great change in endurance in nearly all fatigue tests, so that when we speak of the value given by fatigue tests, it seems we should be sure whether we are speaking of values of stress or of length of endurance.

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[1] In Mr. Farmer's absence, his paper on a "Fatigue Testing Machine" was presented by Mr. H. L. Whittemore.—ED.

[2] See p. 206.—ED.

Mr. Gibson. MR. W. A. GIBSON (*by letter*).—There are several points in Mr. Farmer's apparatus to which I wish to call attention.

In the apparatus for applying load to the specimen I would anticipate considerable trouble due to vibration of the weights. In a White-Souther type of machine which uses a rotating cantilever as a test specimen, considerable trouble of this kind has been encountered. This trouble is due, not nearly so much to the small eccentricity, which will always be found in such a rotating cantilever no matter how much care is taken in centering, as to the vibrations throughout the building. The weights used will get in synchronism with such a vibration, for example, as that caused by an engine test and thus cause wide variations from the calculated stress range. This trouble was originally eliminated by the use of a spring balance and spring. This reduces the actual amount of weight which is liable to this inertia effect and therefore reduces the trouble from this source.

I note that Mr. Farmer has suspended his weights by means of springs, and it may be that by the use of springs of the proper frequency in series with each other, this trouble could be eliminated. The method described above, while eliminating the inertia effects, also introduces an additional trouble caused by variations in the calibration of the spring balance. However, this can be guarded against and proper allowance made for error, which cannot be done with the error due to weights. Results of tests upon an aluminum alloy containing 8 per cent copper show some variations at the higher stresses but the results are, on the whole, fairly uniform. When weights were used to apply the load, the results were entirely inconsistent. For example, a large number of tests having a stress of 16,000 lb. per sq. in. ran for a longer period than some others having stresses of from 9000 to 12,000 lb. per sq. in.

Messrs. Eden, Rose, and Cunningham, at the meeting of The Institution of Mechanical Engineers in London, October 20 and November 17, 1911, described an apparatus very similar to that submitted by Mr. Farmer. In the discussion, they state that they have encountered considerable trouble due to vibrations. They used a scale pan suspended by a spring and placed the weights on the scale pan. In some cases the vibration was sufficient to shake the weights off the pan.

There is another point which I believe is worthy of attention. **Mr. Gibson.** Mr. Farmer has partially covered this in the third paragraph of his conclusions. The method of stress distribution in small round specimens may not agree with that in a complete welded specimen of rectangular shape when the latter is loaded as it would be in an actual machine part. For example, if a bar $\frac{1}{2}$ in. in diameter were turned from a $\frac{3}{8}$-in. plate and then tested, every point on the periphery of the bar at the section of the maximum stress would have equal weight in the test results; thus the material at the neutral axis of the plate would receive equal importance with that at the surface. This would not be the case in the actual mechanism. It seems to the writer that a machine testing the material in the plate as welded would give more nearly the information which the author desires.

In any tests upon rotating beams of steel considerable trouble has been encountered by the writer, due to the corrosion of the holders. Messrs. Eden, Rose and Cunningham also had this trouble. I should like to ask Mr. Farmer if he has encountered any trouble from corrosion.

MR. F. M. FARMER (*Author's closure by letter*).—Referring **Mr. Farmer.** to Mr. Gibson's comment on the matter of vibration, we have found that with spring-suspended weights and with specimens that were carefully turned, there has been no appreciable vibration. In a few tests where there has been considerable vibration, we found that the specimens were eccentric. If, therefore, specimens are properly prepared and the machines are isolated from external vibrations, there ought not to be any trouble from this source. Of course it is obvious that it is necessary to avoid any vibrating of the weights because that introduces periodic excess loading.

In regard to the matter of corroding, we have noticed that corrosion occurs in the holders underneath the weights. We have been unable to explain the cause of this corrosion, but as it is always only on the surface, we have not considered it of any importance so far as the test is concerned, although we have been very anxious to learn the explanation. We find that it frequently develops in a specimen after it has run only a few days.

THE SINGLE BLOW NOTCHED BAR IMPACT TEST AS USED IN THE AMERICAN INDUSTRY.

BY E. H. DIX, JR.

SUMMARY.

This paper has been prepared with a view to increasing the use of the notched bar impact test as a plant control proposition. An attempt has been made to simplify the calibration and use of the three most common current types of pendulum machines. Recommendations have been made which it is hoped will help to standardize this method of testing.

The few results quoted are only a very small fraction of the total number of tests made at the General Laboratories of the Bureau of Aircraft Production (now the Material Section of the Engineering Division at McCook Field) in an effort to standardize the test for that Bureau during the war.

The following conclusions have been reached:

1. The striking distance for the Olsen and Izod machines should be made 0.866 in., and the span of the Charpy machine, 40 mm. (1.575 in.).

2. No broad method of converting results from one machine into terms of another is possible.

3. The use of a square 10 by 10-mm. specimen with a drilled notch 2 mm. in diameter and 5 mm. deep, is recommended.

4. A standard length of specimen for each machine should be adopted, the lengths used in this paper being recommended.

5. It is further concluded that with proper standardization, the notched bar impact test is satisfactory and necessary for plant control, and there is no reason why results of different laboratories obtained on the same type of machine should not check within one or two foot-pounds on identical material.

THE SINGLE BLOW NOTCHED BAR IMPACT TEST AS USED IN THE AMERICAN INDUSTRY.

BY E. H. DIX, JR.

A survey of the work done on the Single Blow Notched Bar Impact Test to date proves conclusively that this method of testing enables one to discover faults in a material which are not shown by the usual static tests, metallographic examination, or chemical analysis. In fact, this test is so sensitive that the early experimenters blamed erratic results on the method of testing. Later developments, however, have shown that if the specimens are carefully prepared and the tests carefully run, the variation in results is due entirely to variations in the specimens tested.

At the outbreak of the war very little commercial use had been made of the impact test in this country. For instance, the first specifications for aircraft materials were written by the International Aircraft Standards Board in Washington, D. C. In regard to the impact tests, they read as follows:

> "When impact testing machines of the pendulum type are available, tests shall be carried out if required to determine the specific impact work of rupture, in foot-pounds (meter-kilograms). Results markedly lower than the average for this type of material will be sufficient cause for further investigation (or re-heat treatment) of the material."

When the U. S. Signal Corps specifications were written, they were practically a repetition of the I. A. S. B. Specifications, but both did, however, specify the type of notch to be used in these tests, and also the size of the cross-section of the specimen. The specimen was given as 10 mm. square, with a notch 5 mm. deep, having a radius of 1 mm. at the bottom. It was stated that this notch might be milled, or else a hole drilled with the proper size drill, and the notch completed with a saw cut. It was also stated that the length of the specimen should be determined by the type of machine used. There were three common types of pendulum machines in use in this country. Two were foreign made; that is, the Izod (English Machine), and the Charpy (French Machine). The Tinius Olsen Testing Machine Co. had two machines on the market; one 400 ft-lb. and one 100 ft-lb. capacity. The 400 ft-lb. machine was too large for general use, but the 100 ft-lb. machine had been in use for about nine years. Owing to war conditions, it was impossible to procure the foreign-made machines. Therefore the manufacture of these machines was started in this country.

The F. H. Bultman Company of Cleveland manufactured the Izod type of machine from drawings received from England. Sauveur and Boylston, Cambridge, Mass., manufactured the Charpy type of machine from drawings made from the original French machine at the Watertown Arsenal.

A different type of specimen had been used with each type of machine, the greatest difference being in the type of notch cut. Results obtained on different types of specimens were not at all comparable, nor were the results obtained on the different types of machines. This made the use of the impact machine very difficult for inspection work, but in spite of these difficulties, it was used to a rather large extent, which is strong evidence of the value of the test.

DESCRIPTION OF MACHINES.

Pendulum Type of Machine.—The machine consists of a pendulum made up of a light shank with a heavy hammer on the end. The pendulum is carried on a shaft, rotating in nearly frictionless ball bearings. The test specimen is held firmly in a vise located at the lowest point of swing of the pendulum. When the pendulum is dropped from a fixed height, it fractures the test specimen and continues on its upward path at the opposite end of its swing. If the motion of the pendulum had not been obstructed by the test piece, the pendulum at the far end of its swing would have reached a point just as high as its starting point, except for a very small loss due to friction. The difference between this height and the height which the pendulum actually reached after having broken the test specimen is a measure of the energy absorbed by the specimen, or its "impact resistance."

The specimen may be either supported as a cantilever, as in the case of the Olsen and Izod machines, or as a simple beam supported at the two ends and loaded in the center, as in the case of the Charpy machine.

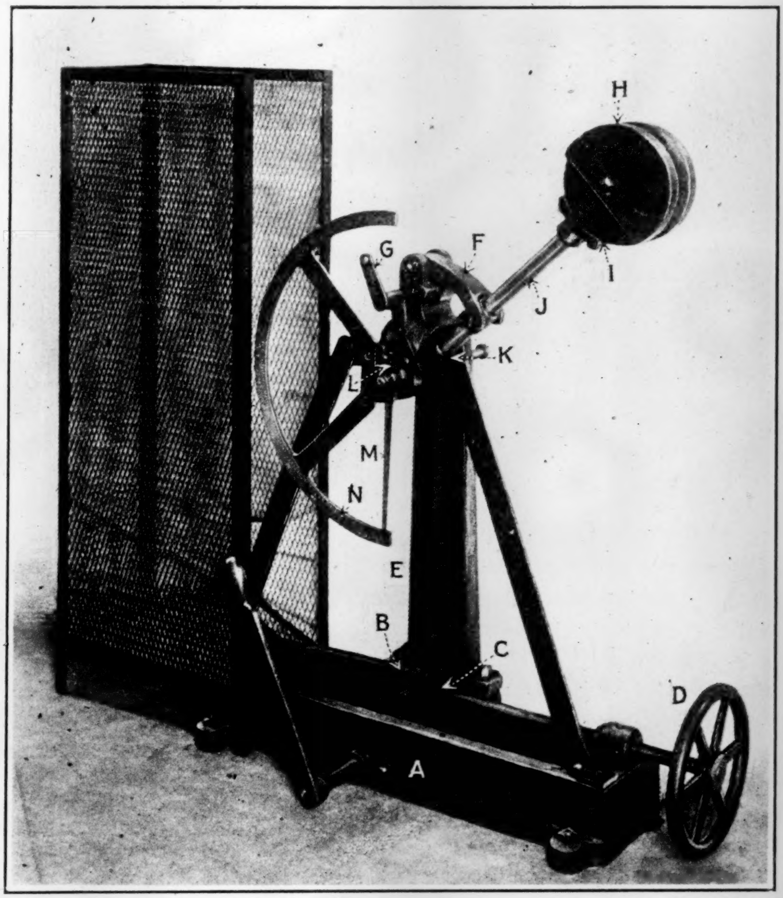


FIG. 1.—Olsen 100 ft-lb. Impact Machine.

Olsen 100 ft-lb. Machine.—A photograph of the machine as used in the General Laboratories of the Bureau of Aircraft Production is shown in Fig. 1. The base *A* of the machine is a large, one-piece casting. The specimen is held in a vise, which is well backed with metal. The backing *B* has a piece of hardened steel inserted to prevent damage when breaking hardened steel specimens. The clamping part *C* of the vise has a rectangular slot of a width just sufficient to allow a small clearance when using a 10-mm. specimen. This part of the vise is pivoted at the bottom, and forced into place by a long ram and hand-wheel *D*. The pendulum support *E* is bolted to the base casting by two machine bolts. This support is a solid casting, with an elbow at the top to hold the shaft of the pendulum. In the original machine, this over-hang was supported only by the two bolts at the base. The bracket shown at the front side of this support was added by our laboratory in an effort to reinforce the pendulum support. This we found to be necessary, inasmuch as if the pendulum were allowed to swing freely, the support could be seen giving up and down with the motion of the pendulum.

The pendulum is held in its raised position by a catch pivoted at the top of the pendulum support, and having fingers to each side of the pendulum shank. This was released by the crank *G*. This method of holding and release was found to be very satisfactory.

The bob of the pendulum *H* is bolted to a casting *I* into which the steel shank *J* is screwed. The upper end of the shank screws into another casting *K*, which fastens on to a shaft rotating with the pendulum. The shaft is carried by frictionless ball bearings in the pendulum support. The end of the shaft carries a small lever *L* which moves the pointer *M* over the graduated scale *N*. The pointer is carried to the highest position that the pendulum reaches after fracturing the specimen, giving a reading direct in foot-pounds. The bob *H* is circular and slit halfway up from the bottom to allow a free swing over the vise. At the top of this slit is located a square hardened steel knife edge, which is well backed by the cast iron. This knife edge is the point of contact between the pendulum and the specimen.

In the first machines made by Olsen, the pendulum support was finished at the bottom, so that the knife edge cleared the top of the vise by just a little over 10 mm. This clearance between the top of the vise and the knife edge will hereafter be referred to as the "striking distance." With the original striking distance, the specimen was bent down flat on the vise, but in doing so the knife edge made a deep gouge in the specimen. This, of course, absorbed some energy. To avoid this error, various users placed filler blocks under the pendulum support in order to make the striking distance greater. Olsen later supplied a filler piece so as to make the striking distance correspond to the English Izod standard of 22 mm. (0.866 in.).

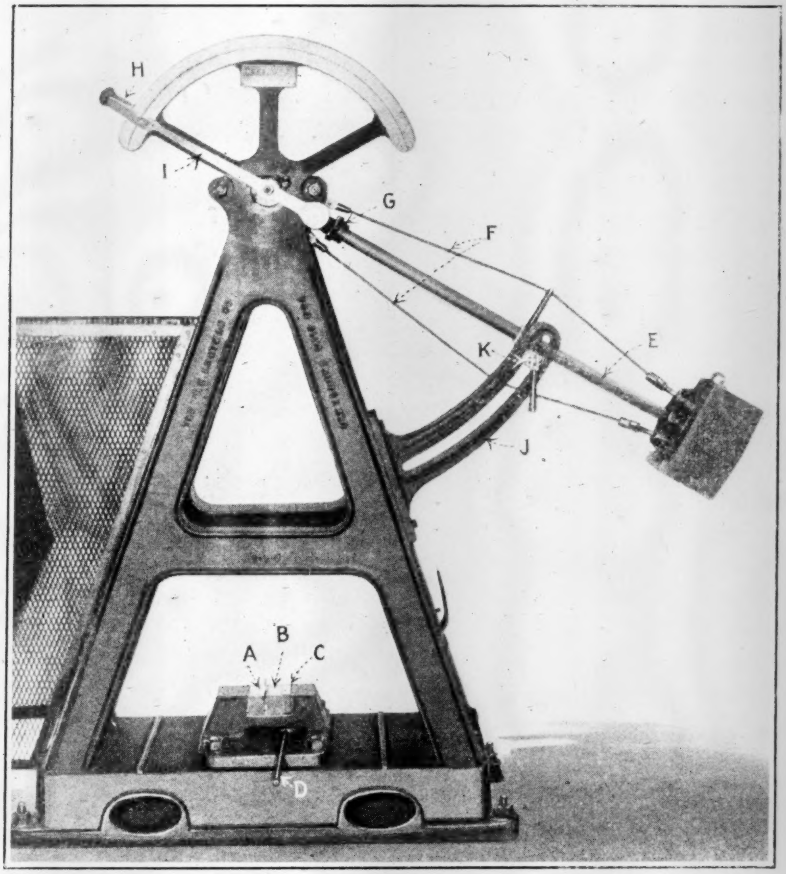


FIG. 2.—Izod 120 ft-lb. Impact Machine.

Izod 120 ft-lb. Impact Machine.—Fig. 2 shows the machine as copied after the original Avery English machine. The two "A" frames are bolted to a heavy base casting and are held at the top by two spacer bolts. A vise is bolted to the base. It carries two hardened steel blocks. The one backing the test piece *A* has a thin rectangular slot cut in it of sufficient width to give a small clearance with the 10-mm. specimen. The other block *B* is straight across and is forced against the test specimen by a wedge *C*, which is operated by a hand wheel and lever *D*. This device is extremely clumsy, and the setting of the test specimen requires a great deal of time.

The pendulum consists of a cast iron bob which is pinned to the end of a hollow steel shank *E*, the upper end of which fits into a threaded steel sleeve. This threaded sleeve carries a casting to which the tie rods *F* are fastened. The sleeve is slotted so that the nut *G* tightens it against the steel shank. The upper end of this threaded sleeve screws into the casting which carries a shaft rotating with the pendulum. The upper end of the casting carries a steel tube *H* which actuates the pointer *I*. In assembling, the split sleeve is first screwed into the casting, which carries the shaft. The small casting holding the tie rods is held in place loosely by two lock nuts. By adjusting these lock nuts, the steel shank is drawn up until the striking distance is the desired value of 22 mm. A hole is then drilled through the shaft casting, the threaded sleeve and the hollow tube, after which a large pin is driven through the three, so that there is no possibility of the adjustment of this machine being changed except by grinding the knife edge. This makes it necessary to put in a new knife edge instead of re-grinding the old one should it become worn.

The pendulum shaft rotates in frictionless ball bearings carried in the "A" frames. The pendulum is held in its raised position by a bracket *J* projecting from one "A" frame. The releasing mechanism *K* may be adjusted anywhere along this bracket, but for all of the work done at our laboratory, this was locked so as to give an energy of blow equal to 120 ft-lbs. The release holds on only one side of the shank and is rather unsatisfactory, for the reason that there is a tendency to vibrate the shaft when releasing it. When the height of fall is properly set, the dial reads directly in foot-pounds.

Charpy 30 m-kg. (217 ft-lb.) Impact Machine.—This machine as manufactured by Sauveur & Boylston is shown in Fig. 3. It is different from the original French machine at the Watertown Arsenal only in several unimportant details. The two castings supporting the pendulum are bolted to a heavy base casting.

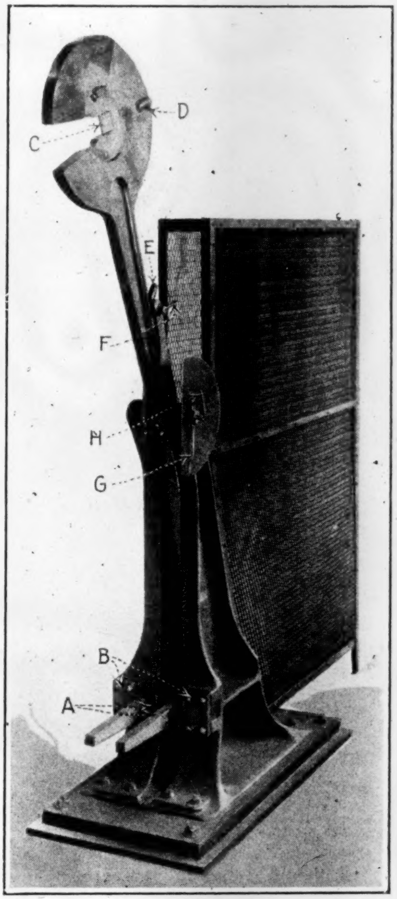


FIG. 3.—Charpy 30 m-kg. Impact Machine.

These castings carry frictionless ball bearings, on which the pendulum shaft rotates. The specimen is placed on the two hardened steel anvils *A* from which project the long ends shown in the forepart of the photograph. These two anvils are held in place by two plates *B* so that they may be adjusted to any length of span.

The pendulum is a solid steel casting with a hardened steel knife edge *C* in the center. The shank of the pendulum is an I-beam section. The pendulums are machined as closely as possible to drawing, but the constants, such as weight, radius to center of gravity, and height of fall of the center of gravity, are determined separately for each pendulum. The hardened steel knife edge is made with an angle of 30 deg., the point being rounded to a diameter of 0.120 in. in the case of the machine in our laboratory. This knife edge strikes the center of the impact specimen on the side opposite the notch and fractures it as a beam.

TABLE I.—COMPARATIVE DATA ON IMPACT TESTING MACHINES.

Type...............	Olsen.	Izod.	Charpy.
American Manufacturer............	Tinius Olsen & Co , Philadelphia, Pa.	F. H. Bultman, Cleveland, O.	Sauveur & Boylston, Cambridge, Mass.
Capacity, ft-lb..................	100	120	217 (30 m-kg.)
Weight, lb......................	500	1200	600
Floor Space (Actual), in............	16 by 51	14 by 53	19 by 34
Including Swing of Pendulum....	16 by 52	14 by 96	19 by 69
Height, in......................	48	80	53
Striking Distance,[1] in..............	0.404[a]	0.866	....
Distance between Supports (span), in..	....	....	1.575 (40 mm.)
Distance between Sides of Anvil, in...	....	....	2.25
Approximate Weight of Hammer, lb...	38	70	50.9 (23.08 kg.)
Height of Fall of Center of Gravity, ft.	2.63	1.91	4.43 (134.8 cm.)
Radius to Center of Gravity, in......	18.4	....	27.3 (69.3 cm.)
Linear Velocity of Center of Gravity, ft. per sec......................	13.01	10.50	16.25

[1] Clearance between knife edge and top of vise.

[a] As supplied by manufacturer without liner; with liner, 0.866 in.

Besides the transverse test, this machine is adapted for impact tension tests. A specimen with threaded ends is screwed into a threaded hole *D* in the back of the pendulum. A steel hammer block is screwed on to the outer end of the specimen. When the pendulum falls, the hammer block strikes on the two projecting legs, and the test specimen is broken.

The pendulum is held in its raised position by a small catch *E* carried by two brackets attached to the top of the pendulum supports. It is released by the trigger *F*. The releasing mechanism is very satisfactory. The pointer, *G* is actuated by a small lever H carried in the end of the rotating shaft. The dial over which the pointer moves is graduated in degrees, therefore the energy absorbed must be computed from the degree reading and from the constants which are marked on each individual pendulum. For a laboratory it is convenient to make a table, giving the energy absorbed for each degree reading in foot-pounds and meter-kilograms.

Comparative Data.—The comparative data in Table I will be found convenient.

CALIBRATION OF MACHINES.

Center of Percussion.—In order that no energy be lost in heat due to vibrations set up in the pendulum and shaft, the knife edge should be located exactly at the center of percussion of the pendulum. This is a matter of design, but may very easily be checked in a laboratory. If T is the time of one swing, that is, from one extreme position to the other, and l is the length from the center of suspension to the center of gravity, then $T=\pi\sqrt{\frac{l}{g}}$. This hold only for angles of say less than 8 deg. between the vertical and the highest point of the pendulum. T may be determined very simply, and from this the length l calculated.

Center of Gravity.—The radius from the center of suspension to the center of gravity must be known in order to calculate the height of fall of the center of gravity. This may be determined experimentally as follows:

First, weigh the pendulum, including all parts which rotate with it. Then, with the pendulum assembled in the machine, determine the force necessary to hold it in a horizontal position at any convenient distance from the center of suspension. This force multiplied by the lever arm, will equal the total weight of the pendulum multiplied by the radius to the center of gravity.

Dial Graduations.—If the radius to the center of gravity is known, the height of fall from any given position may be calculated, and the energy of the blow is then the product of the height of fall by the weight of the pendulum. The energy remaining after fracturing the test specimen is equal to the weight of the pendulum multiplied by the height to which the center of gravity rises. The difference between this energy and the original energy of the blow should be indicated on the dial. In this way the dial graduations may be checked.

Setting of Machine.—The foundation of the machine should be very secure. In the writer's opinion, no reliable results can be obtained unless the machine is bolted securely to a concrete foundation. In setting up, the machine should be leveled so that the rotating shaft is in a horizontal position. The machine should be leveled in a direction perpendicular to the shaft, so that the pendulum in hanging free just touches a 10 mm. specimen in place in the vise.

Striking Distance or Span.—In the Olsen and Izod machines, the striking distance is of the utmost importance, because this gives the lever arm over which the specimen is fractured. This distance cannot be altered in the Izod machine after it is once set except by grinding or mutilating the knife edge, but it is very important that this be checked. The only accurate way of checking this distance is by making a hardened steel gage of the exact dimensions required. This gage should just slip between the knife edge, when the pendulum is hanging free, and the top of the vise.

In the Olsen machine, it is possible to adjust this striking distance to any value desired by simply varying the thickness of the filler block under the pendulum support. For reasons which will be discussed later, the writer desires to recommend that the striking distance in this machine be maintained at 22 mm. (0.866 in.) to correspond with the Izod machine.

In the Charpy machine, the test specimen is supported at the two ends. The span is adjusted by moving the two anvils *A*, Fig. 3. These should be adjusted so that the knife edge swings exactly equally distant between the two. This may be done by the jig shown in the lower left-hand corner of the photograph of Fig. 4. This jig is copied after one used by Captain Philpot in England. A notch is cut in one side, so as to conform to the knife edge. The center of this slot is in the center of the tongue, which fits between the anvils, the length of the tongue being exactly 40 mm. (1.575 in.). This is the span used on the original French machine at the Watertown Arsenal.

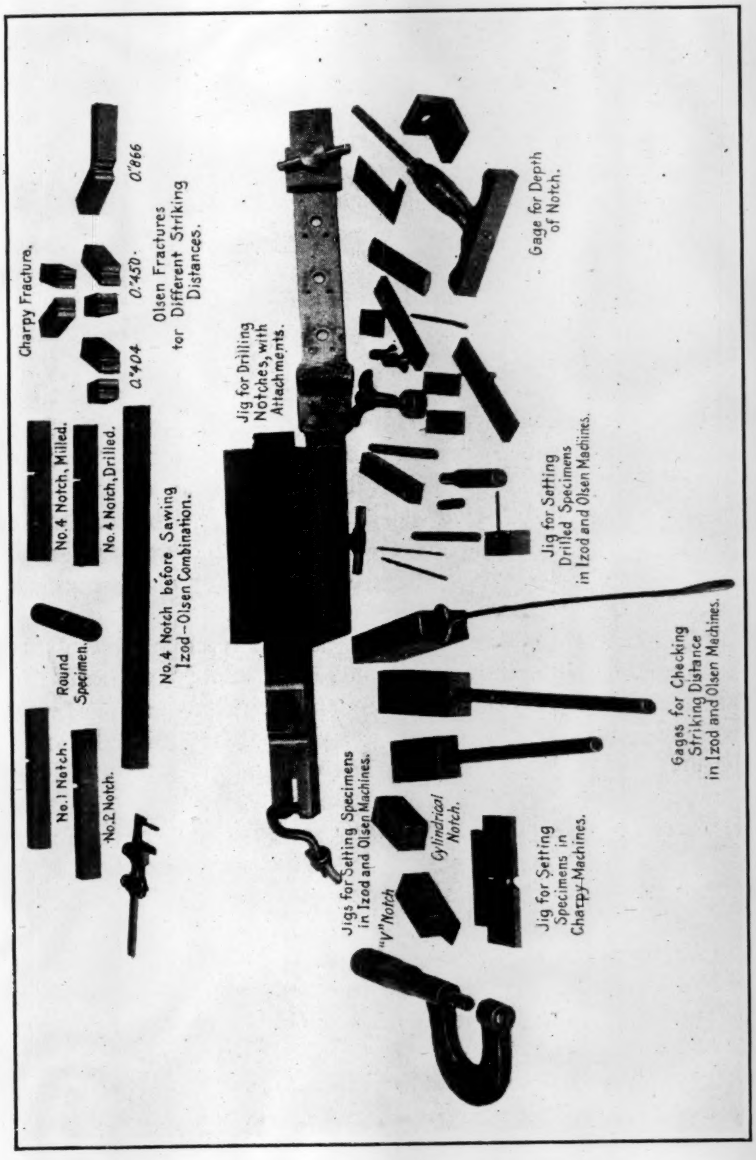

No. 1 Notch.
No. 2 Notch.
Round Specimen.
No. 4 Notch, Milled.
No. 4 Notch, Drilled.
No. 4 Notch before Sawing Izod-Olsen Combination.
Charpy Fracture.
0."404
0."450
0."866
Olsen Fractures for Different Striking Distances.
Jig for Drilling Notches, with Attachments.
Gage for Depth of Notch.
Jig for Setting Drilled Specimens in Izod and Olsen Machines.
Gages for Checking Striking Distance in Izod and Olsen Machines.
Jigs for Setting Specimens in Izod and Olsen Machines.
"V" Notch
Cylindrical Notch.
Jig for Setting Specimens in Charpy Machines.

FIG. 4.—Views of Miscellaneous Apparatus, Jigs, etc.

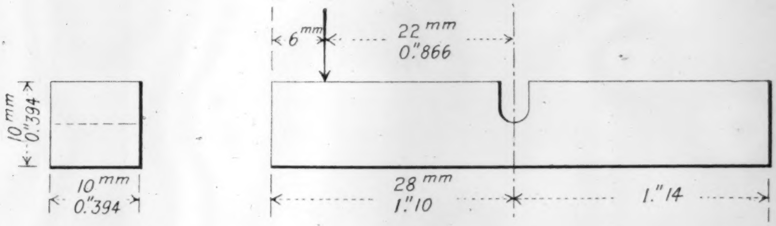
Condition of Knife Edge and Vise Blocks.—The condition of the knife edge should be carefully examined. It should be kept sharp and square. In order to have it maintain its edge, it is necessary that it should be as hard as consistent with the necessary toughness. Should it be necessary to regrind the edge, it should be checked to see if it touches the specimen all along its width, and that it is adjusted to the proper striking distance. The vise blocks should not be allowed to become rounded, particularly the one which backs the specimen. It must be borne in mind that grinding these blocks changes the striking distance. When measuring the striking distance, the back of the vise should be used rather than the front part, because this is the edge over which the specimen is broken.

Friction.—The ball bearings, if kept in proper condition, are practically frictionless. However, if a stiff grease is used or if dust is allowed to accumulate, this friction may reach a point where it will cause considerable error in the results. The friction may be easily checked by allowing the pendulum to drop freely from its raised position. Repeated swings should not fall lower than say from $\frac{1}{2}$ to 1 ft-lb. for each complete swing.

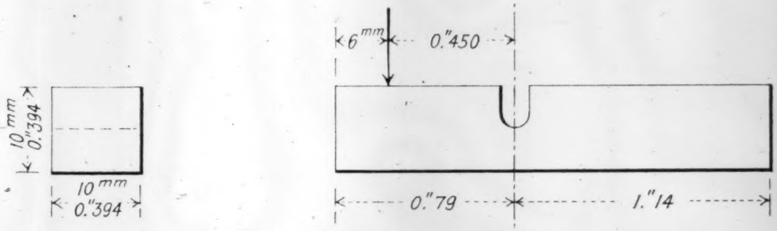
The Three Machines in Detail.—In the manufacture of the Olsen machine, the pendulum is made up roughly, according to drawing. It is then assembled in the machine, and the pendulum supported in a horizontal position at the knife edge on a platform scale. The material is then chipped from the inside of the bob until the weight on the scale is shown to be $33\frac{1}{3}$ ft-lb. The releasing mechanism is then adjusted, so that the height of fall of the knife edge is exactly 3 ft. It may be readily proven by moments that the total energy of the blow is then 100 ft-lb.

The correct weight of pendulum of the Izod machine is obtained just as in the case of the Olsen machine. The releasing mechanism may then be set so that when the pendulum swings freely it indicates 120 ft-lb. on the dial. A calibration test should then be made so as to check the dial reading, as previously explained.

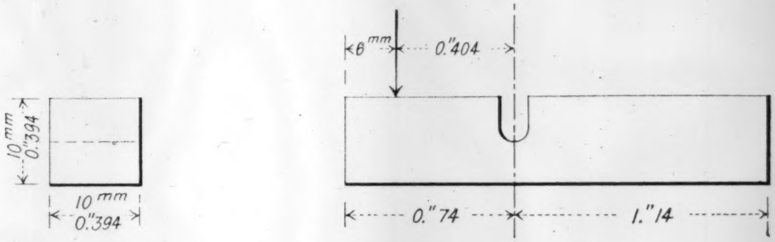
The calibration of the Charpy machine requires little comment aside from what has already been given. The greatest chance for error occurs in the little lever which moves the needle over the dial. This lever is carried on the end of the rotating shaft, and held in place by a small set screw. It is round and therefore should be spotted where the set screw tightens against


10 mm
0."394
10 mm
0."394
6 mm
22 mm
0."866
28 mm
1."10
1."14

Striking Distance 0.866 in.


10 mm
0."394
10 mm
0."394
6 mm
0."450
0."79
1."14

Striking Distance 0.450 in.


10 mm
0."394
10 mm
0."394
6 mm
0."404
0."74
1."14

Striking Distance 0.404 in.

FIG. 5.—Test Specimens for Olsen Machine.

it. It is, however, of very light construction, and can easily be bent out of position. This may be checked by allowing the pendulum to hang free. The lever should just touch the pointer when set on zero degree.

TYPES OF SPECIMENS.

Shape of Section.—The specimen for the notched bar impact test is, as its name implies, essentially a bar, notched so that there is a sudden change in section. It is a well-known fact that an abrupt change of section produces a serious weakening effect in a machine part and is avoided wherever possible. It is, however, not always possible to avoid this difficulty. A very notable example is that of the screw thread employed in all types of machines. Just why the notched type of specimen has come into such general use has never been thoroughly explained. The first experimenters tried a specimen of equal section throughout. Later they changed to the notched section, and this specimen has been used ever since. This much may be said: The notched bar test discovers a property of the material which has become recognized as of very vital importance.

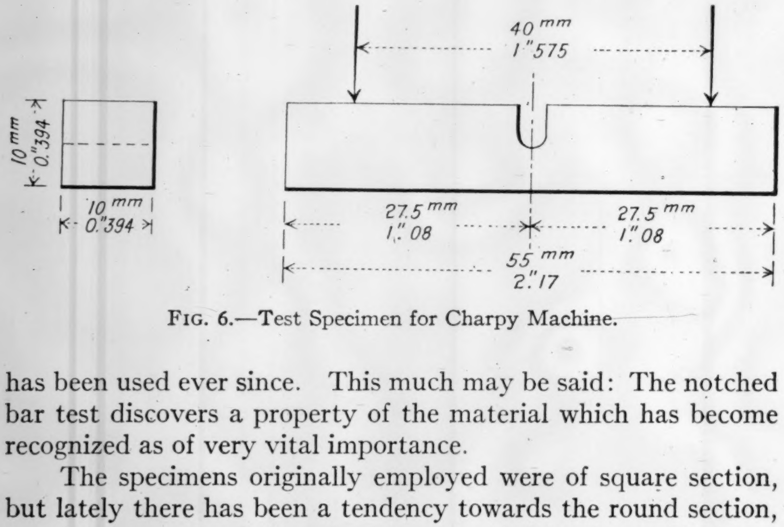


FIG. 6.—Test Specimen for Charpy Machine.

The specimens originally employed were of square section, but lately there has been a tendency towards the round section, for the reason that it is easier to prepare. The General Laboratories did considerable work in connection with the round specimen, and we came to the same conclusions as arrived at by a number of other experimenters, namely, that the round section gives just as good results as the square section. No tests on round specimens are included in this paper. All of the specimens were of square section 10 by 10 mm.

Type of Notch.—Almost every conceivable type of notch has been experimented with. The notches used at our laboratory

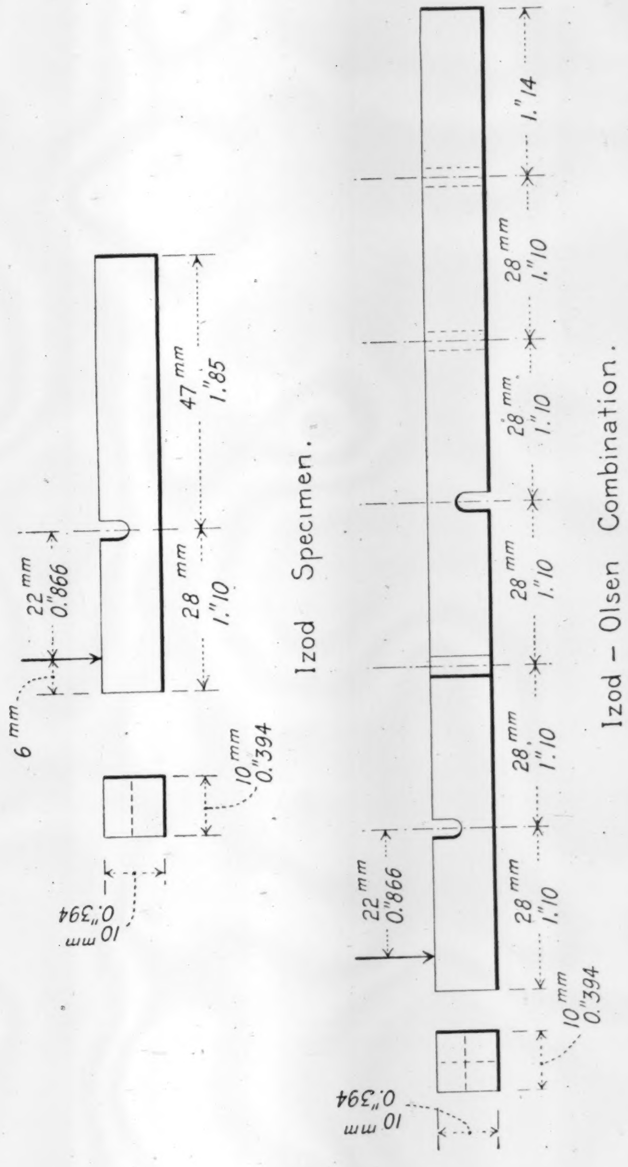
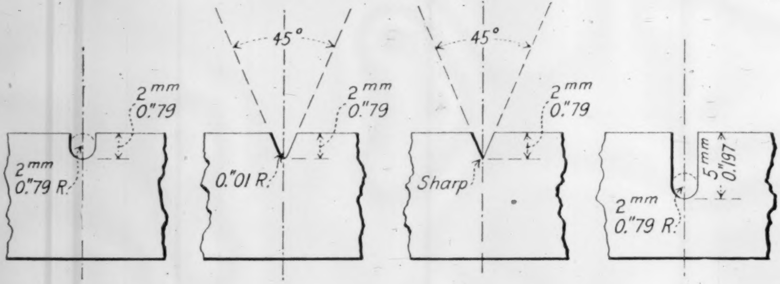

Izod Specimen.
6 mm
22 mm
0."866
28 mm
1."10
47 mm
1."85
10 mm
0."394
10 mm
0."394
Izod - Olsen Combination.
22 mm
0."866
28 mm
1."10
28 mm
1."10
28 mm
1."10
28 mm
1."10
28 mm
1."10
1."14
10 mm
0."394
10 mm
0."394

FIG. 7.—Test Specimen for Izod Machine; Izod-Olsen Combination.

are shown in Fig. 8. Notch No. 2 is the one originally employed by Izod, and is generally known as the Izod Standard Notch. This notch has a radius of 0.01 in. at the bottom. Notch No. 2-A is the same as No. 2, except that the "V" is sharp at the bottom, no radius being used. Notch No. 4 is the one given in the Bureau of Aircraft's specifications. This notch may be either drilled, and then completed with a saw, or else cut with a formed milling cutter. Notch No. 1 is the same as No. 4, except that its depth is the same as that of Notch No. 2.

Length of Specimen.—In regard to the length of specimen, there seems to be very little uniformity in American practice. For this paper, the length of the Izod specimen was made the same as that originally employed by Izod. The length of 47 mm. below the center of the notch is unimportant, but the length of 28 mm. above the notch is very important. For a striking distance of 22 mm. this gives a distance above the striking point of 6 mm. It is readily seen that the angle through which the specimen must bend before the knife edge clears it is determined by the length above the striking point.



No. 1. No. 2. No. 2-A. No. 4.

Fig. 8.—Types of Notches.

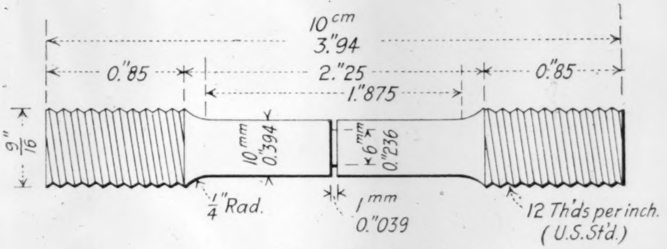
For the sake of uniformity, the same distance above the striking point was employed for specimens to be tested in the Olsen machine. Thus, for different striking distances we had specimens of different lengths, as shown in Fig. 5. The length below the center of the notch in the Olsen specimen had to be made shorter than that of the Izod machine, in order that the

ERRATA.

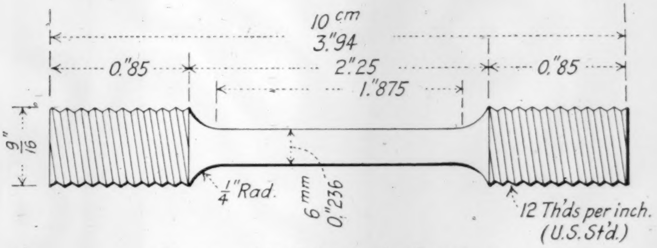
The dimensions 0.79 in. in Fig. 8, page 736, should read 0.079 in.—ED.

specimen would fit in the notch cut in the vise of the Olsen machine.

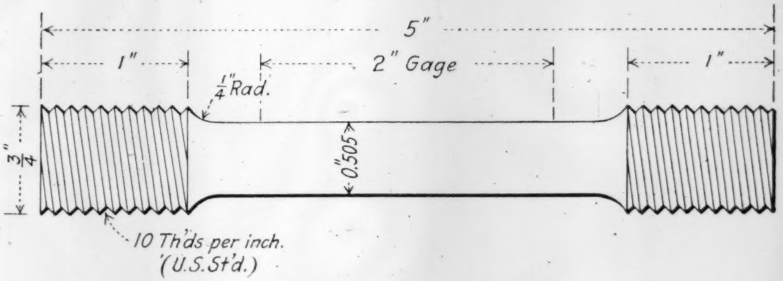
The length of the Charpy specimen was made to conform to the standard used at the Watertown Arsenal, namely, 55 mm.


10 cm
3."94
0."85
2."25
0."85
1."875
9/16"
10 mm
0."394
6 mm
0."236
1/4" Rad.
1 mm
0."039
12 Th'ds per inch.
(U.S. St'd.)

Charpy Notched Specimen.


10 cm
3."94
0."85
2."25
0."85
1."875
9/16"
1/4" Rad.
6 mm
0."236
12 Th'ds per inch.
(U.S. St'd.)

Charpy Un-Notched Specimen.


5"
1"
2" Gage
1"
1/4" Rad.
3/4"
0."505
10 Th'ds per inch.
(U.S. St'd.)

B.A.P. 0."505 Tension Specimen.

FIG. 9.—Tension Test Specimens.

(Fig. 6). For the machine in our laboratory, this gave a clearance of 0.045 in. between each end of the specimen and the sides of the anvil, this being true only when the span was set at 40 mm.

Finish.—Some of the experiments covered by this paper were made to determine the effect of the degree of finish of the specimens. For all other tests, the specimens were ground exactly to size.

Olsen-Izod Combination Specimen.—In order to obtain a very close comparison of the results obtained on the Olsen and Izod machines, a combination specimen was made, as shown in Fig. 7. The base of this specimen is made to conform to the Olsen machine, for, owing to the construction of the machine, it is not possible to have the specimen project downward any further than this length. In the case of the Izod machine, it is possible to have the specimen project down as far as desired. Therefore, it is possible to obtain four breaks in the Izod machine having the notch on each of the four sides of the specimen. The specimen is then put in the Olsen machine and broken, the notch in this case being on the same side as the last notch broken in the Izod machine.

Tension Test Specimens.—Fig. 9 shows the notched and un-notched Charpy tension test specimen used in these experiments. These dimensions are taken directly from the standards used at the Watertown Arsenal.

MATERIAL.

Selection.—Of the large number of tests made at the General Laboratories, it is possible to include only a very few in this paper. The results selected from this mass of data have been chosen with a view to proving some of the most important points which the writer has taken up in this discussion. Only two lots of material have been selected. A nickel-chrome steel, received in $\frac{5}{8}$-in. rounds which were rolled from one ingot, and twelve connecting rods, all from the same heat of steel and forged at the same time. This material will be taken up in detail below.

Nickel-Chrome Steel.—The Chemical analysis of this steel is as follows:

Carbon	0.39	per cent
Manganese	0.49	"
Phosphorus	0.015	"
Sulfur	0.014	"
Silicon	0.31	"
Nickel	3.54	"
Chromium	0.73	"

The bars were quenched from 1500° F. into oil and then drawn at 1100° F.

The bars were all rolled from the same ingot, and were received in our laboratory in three lengths totaling 24½ ft. They were then cut up into 27-in. lengths, and each given a bar number. Each of these rods was then prepared into a number of specimens,

TABLE II.—NUMBER AND TYPES OF NICKEL-CHROME STEEL SPECIMENS.

BAR NO.	NUMBER OF SPECIMENS.	TYPE OF SPECIMENS.
1	1	Standard 0.505-in. Tension.
2	2	Charpy Notched Tension (A and B).
3	2	Charpy Unnotched Tension (A and B).
4	5	Olsen No. 1 Impact (0.866 in.).
5	2	Izod and Olsen Combination No. 1 Notch.
6	5	Charpy No. 1 Impact.
7	1	Standard 0.505-in. Tension.
8	2	Charpy Notched Tension (A and B).
9	2	Charpy Unnotched Tension (A and B).
10	5	Olsen No. 2 Impact (0.866 in.).
11	2	Izod and Olsen Combination No. 2 Notch.
12	5	Charpy No. 2 Impact.
13	1	Standard 0.505-in. Tension.
14	2	Charpy Notched Tension (A and B).
15	2	Charpy Unnotched Tension (A and B).
16	5	Olsen No. 2-A (0.866 in.).
17	2	Izod and Olsen Combination No. 2-A Notch.
18	5	Charpy No. 2-A Impact.
19	1	Standard 0.505-in. Tension.
20	2	Charpy Notched Tension (A and B).
21	2	Charpy Unnotched Tension (A and B).
22	5	Olsen No. 4 Impact (0.866 in.).
23	2	Izod and Olsen Combination No. 4 Notch.
24	5	Charpy No. 4 Impact.
25	1	Standard 0.505-in. Tension.
26	2	Charpy Notched Tension (A and B).
27	2	Charpy Unnotched Tension (A and B).
28	2	Rectangular Unnotched Charpy.
29	2	Rectangular Unnotched Olsen.
30	2	Rectangular Unnotched Izod.
31	2	Square Unnotched Charpy.
32	2	Square Unnotched Olsen.
33	2	Square Unnotched Izod.

and designated by A, B, C, etc. Each specimen therefore will bear the bar number and the letter of the specimen. For instance, No. 4-B would mean the second specimen cut from bar No. 4. In Table II is given a tabulation showing the number and types of specimens cut from each bar.

Transverse impact specimens were all carefully ground exactly to dimension, and the length above the notch was held to a tolerance of 0.005 in. The notches were cut with a milling cutter. The cylindrical notches were all drilled, except as will be explained later.

The tension impact specimens were made up according to Fig. 9, except that the ones intended to be subjected to a static test were made with threaded ends to fit standard laboratory tension specimen holders. These bars were marked "A." Tension bars, marked "B," were made with threaded ends, to fit the Charpy machine. Care was taken that both of these types of specimens could be screwed into the holders clear up to the end of the thread. This was very important, so that there would be the same amount of material in each case to absorb the energy. The 0.505-in. tension specimens were made up according to the B. A. P. standard.

Forged Connecting Rods.—In order to obtain results on actual forged parts, 12 connecting rods of nickel-steel were selected. The heat analysis on these rods is tabulated below:

Carbon	0.40	per cent
Manganese	0.58	"
Phosphorus	0.031	"
Sulfur	0.020	"
Silicon	0.108	"
Nickel	1.36	"
Chromium	0.68	"

Six of these rods, laboratory Nos. 8188–93, had been annealed for one hour at 1450–1475° F., this annealing being done in order to make possible the trimming of the rods. The other six rods, laboratory Nos. 8194–99, had been annealed for one hour at 1450–1475° F., and then heated to 1440° F., held for 30 minutes, quenched in hot water at 140° F., until they cooled to a temperature of 300–400° F., and were then put immediately into the drawing furnace and left for one hour at 1000–2500° F.

Fig. 10 shows a sketch of a connecting rod, giving the location of the specimens. Four specimens, Nos. 1 to 4, were cut from the flat end of the connecting rod. These were used to determine relations between the three different striking distances on the Olsen machine, and to compare these results with the Charpy machine. The straight shank of the rod was used for tension specimens. A few impact specimens were also cut from the shank, in order to give an idea of the variation of the impact value obtained from different parts of the connecting rod.

Three specimens, Nos. 9, 10, and 11, were cut from the boss. These were used to determine what effect the degree of finish had on the results, to compare the milled notch with the drilled notch, and to study the effect of different lengths above the striking point in the Olsen and Izod machines, as well as the effect of different length specimens in the Charpy machine.

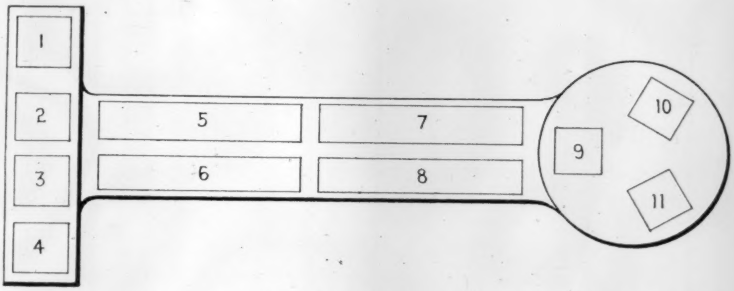


FIG. 10.—Location of Specimens from a Connecting Rod.

PREPARATION OF SPECIMENS.

The high cost and the long time required for the preparation of impact specimens is the greatest drawback to the test, and therefore considerable effort has been devoted to the best method of preparation of impact specimens. A great portion of this work was done by Mr. James W. Swoger, foreman of the machine shop of the General Laboratories. In the early stages of our work at the laboratory, all of the specimens were prepared in the milling machine. They were usually smoothed off with a file in order to give a good finish. Later we did the rough machining in the shaper, and finished them on the milling machine, or in some instances simply with a file. Towards the latter part of our investigation we were able to procure a surface grinder and then all of the specimens were finished by grinding. The specimens used in experiments discussed in this paper were all ground to size, except special ones, as has already been noted.

The cutting of the notch presents much greater difficulties than the preparation of the specimen. In our work, the "V" notches were always cut with a milling cutter, the depth of the notch being regulated by the dial on the milling machine. At first the notches with cylindrical bottoms were cut with a formed milling cutter. Later Mr. Swoger designed a jig whereby the notch could be accurately located and drilled. This jig is shown in the center of the photograph in Fig. 4. All of the cylindrical notches reported in this paper were drilled with this jig, except in special cases where it was desired to compare the drilled notch with the one cut by a formed milling cutter.

METHOD OF TESTING.

Measurements Taken.—Although all specimens were carefully checked for dimensions before leaving the machine shop, they were also measured in the laboratory, and the following dimensions recorded:

1. The length above the center of the notch;
2. The width across the slot;
3. The width from front to back;
4. The thickness back of the slot.

Precautions Taken.—The striking distance was always checked and the condition of the knife edge examined before making any test. The hardened steel gages used for checking the striking distance are shown in the center of the photograph in Fig. 4. The pendulum was also allowed to swing free in order to see that the friction was not excessive.

Methods of Setting Specimens.—In Fig. 11 are given sketches showing the way the specimens were set in the different types of machines. In the Olsen and Izod machines, the specimen was located by means of jigs, which consisted of a small block of steel with a foot on the end. For the "V" notch, this foot was made with an angle equal to one-half the angle of the "V."

For the cylindrical notch, the foot was made of just one-half the thickness of the notch. For the drilled cylindrical notch, another type of jig was used, consisting of a block in which a piece of drill rod had been soldered. The bottom of the block and the drill rod were then filed until the rod was just half the thickness of the drilled hole in the specimen. All of these jigs are shown in Fig. 4.

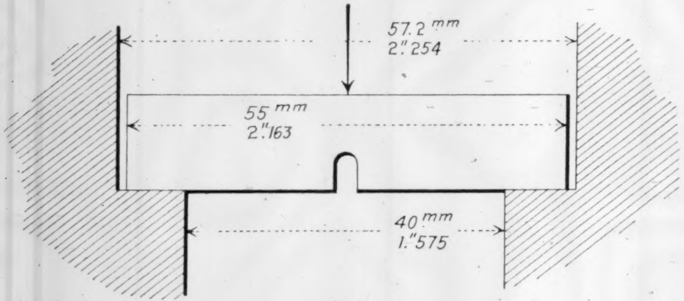
The jig used for setting a specimen in the Charpy machine was of a different type. It is shown in the lower left-hand part of Fig. 4. The tongue of this jig just slipped in between the two anvils supporting the specimen. The projections on each side of the tongue fitted against the portion of the anvils over which the specimen was broken. The specimen was placed on the anvils, and the jig laid on top of it. By looking through a slit in the jig, it was possible to locate the notch of the specimen exactly in the central position. The notch in the back of this jig was used for locating the anvils so as to have the knife edge exactly in the middle of the span.

Fig. 11 shows the method of holding the rectangular unnotched specimens in the Olsen and Izod machines.

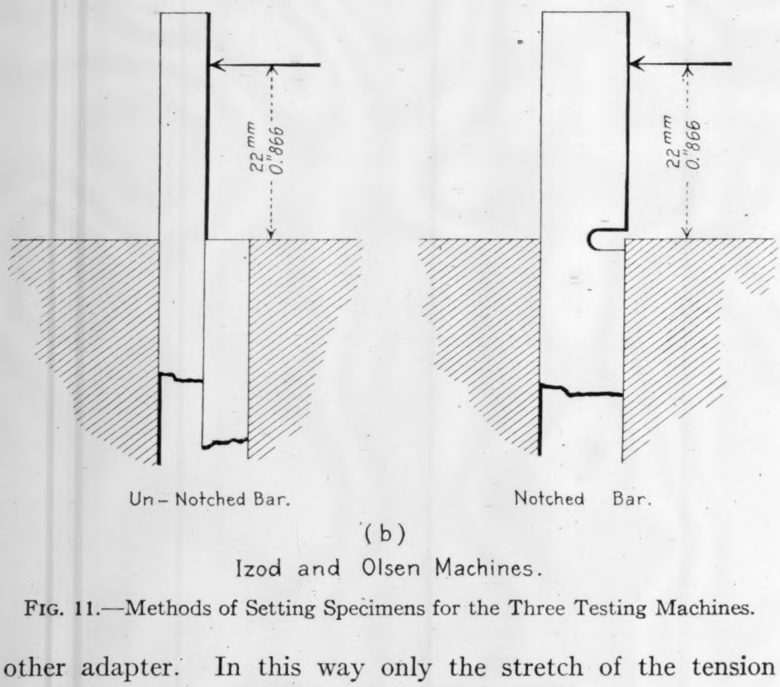
Tension Tests on Charpy Machine.—In making the impact tension tests on the Charpy machine, great care was taken to see that the bars were screwed into their holders exactly the same distance each time, this being necessary so that there was always the same amount of metal to absorb energy. Tests were made on both the notched and unnotched specimens.

Static Tension Tests.—Static tension tests were made on standard 0.505-in. threaded end tension specimens, in self-aligning adapters. Readings of load and deformation were taken for small increments. The deformation was measured by means of a Reihle Bros. 2-in. extensometer.

In order to compare the energy absorbed in breaking a specimen in the static test, with that required in the impact test, specimens were made up which were duplicates in every way of the ones tested on the Charpy machine, except that the threaded ends were made to fit the standard self-aligning adapters for the tension machine. These were tested in an Olsen 50,000-lb. tension testing machine and readings of load and deformation taken for small increments. Deformation in this case was obtained by means of an Ames dial which measured the distance between the adapters. The dial was attached very close to the end of one adapter. It touched a pin screwed in to the end of the other adapter. In this way only the stretch of the tension specimen was measured. Stress-deformation curves were plotted and the area under the curve measured by a planimeter.



(a)
Charpy Machine.



Un-Notched Bar. Notched Bar.

(b)
Izod and Olsen Machines.

FIG. 11.—Methods of Setting Specimens for the Three Testing Machines.

From this area the total energy required to break the specimen was calculated.

TABULATION OF RESULTS.

The results of the tests on the two lots of material previously mentioned are given in Tables III to XIV:

TABLE III.—TESTS OF IZOD-OLSEN COMBINATION SPECIMENS.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. No. 9630.
STRIKING DISTANCE 0,866 IN.
ALL VALUES ARE ENERGY ABSORBED IN FOOT-POUNDS.

Izod.	Olsen.	Izod.	Olsen.	Izod.	Olsen.	Izod.	Olsen.
Notch No. 1.				Notch No. 2.			
Specimen No. 5-A.		Specimen No. 5-B.		Specimen No. 11-A.		Specimen No 11-B.	
38		37		21		25	
39		37		21		22	
38		37		24		23.5	
37		33		23		20	
Aver. .38	37	36	38	22.4	22.5	21.4	22
Notch No. 2-A.				Notch No. 4.			
Specimen No. 17-A.		Specimen No. 17-B.		Specimen No. 23-A.		Specimen No. 23-B.	
20		22		17.5		18.5	
20		20		17		17	
23.5		20		19		17.5	
21		20		....		18.5	
Aver. .21.1	18.5	20.5	19	17.8	19	17.9	16

TABLE IV.—COMPARISON OF TYPES OF NOTCHES, OLSEN MACHINE.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. No. 9630.
STRIKING DISTANCE, 0.866 IN.
ALL VALUES ARE ENERGY ABSORBED IN FOOT POUNDS.

Specimen No.	Notch No. 1.	Specimen No.	Notch No. 2.	Specimen No.	Notch No. 2-A.	Specimen No.	Notch No. 4.
4-A.........	37.5	10-A......	26	16-A......	19.5	22-A......	27.5
4-B.........	36.5	10-B	28	16-B......	19.5	22-B......	17.5
4-C.........	40	10-C......	27.5	16-C......	19	22-C......	25
4-D.........	38	10-D......	25.5	16-D......	19.5	22-D......	31
4-E.........	40	10-E......	26	16-E......	18	22-E......	19
Aver......	38.4	Aver....	26.6	Aver....	19.1	Aver....	24.0

TABLE V.—COMPARISON OF TYPES OF NOTCHES, CHARPY MACHINE.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. NO. 9630.
ALL VALUES ARE ENERGY ABSORBED IN FOOT POUNDS.

Specimen No.	Notch No. 1.	Specimen No.	Notch No. 2.	Specimen No.	Notch No. 2-A.	Specimen No.	Notch No. 4.
6-A..........	41.2	12-A......	24.8	18-A......	22.7	24-A......	21.4
6-B..........	41.7	12-B......	23.6	18-B......	22.7	24-B......	24.1
6-C..........	....	12-C......	23.4	18-C......	20.7	24-C......	24.8
6-D..........	38.4	12-D......	27.5	18-D......	20.7	24-D......	....
6-E..........	40	12-E......	25.9	18-E......	21.4	24-E......	26.3
Aver......	40.3	Aver....	25.0	Aver....	21.6	Aver....	24.1

TABLE VI.—COMPARISON OF MACHINES, UNNOTCHED SPECIMENS.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. NO. 9630.
ALL VALUES ARE ENERGY ABSORBED IN FOOT POUNDS.

OLSEN.[1]		IZOD.		CHARPY.		
Specimen No. No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen m-kg.
SECTION 0.394 BY 0.197 IN.						
29-A..........	77	30-A......	54	28-A.........	105.0	14.5
29-B..........	78	30-B......	51	28-B.........	110.0	15.2
Aver........	77.5	Aver....	52.5	Aver......	107.5	14.85
SECTION 0.197 BY 0.197 IN.						
32-A..........	33.5	33-A......	23.5	31-A.........	76	10.5
32-B..........	33.5	33-B......	22.5	31-B.........	78.5	10.9
Aver........	33.5	Aver....	23.0	Aver......	77.3	10.7

[1] Striking distance, 0.866 in.

TABLE VII.—COMPARISON OF MACHINES: DATA FROM TABLES III, IV AND V.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. NO. 9630.
ALL VALUES ARE ENERGY ABSORBED IN FOOT POUNDS.

Notch No.	Olsen, Ft-lb.	Izod, Ft-lb.	Charpy,	
			Ft-lb.	m-kg.
1................	38.4	38	40.3	5.5
2................	26.6	22.4	25.0	3.4
2-a..............	19.1	21.1	21.6	3.0
4................	24.0	17.8[a]	24.0	3.3

NOTE.—Results on Olsen and Charpy machines are average of 5 tests; on Izod machines, average of 4 tests.
[a] See page 750.

DISCUSSION OF RESULTS.

Effect of Varying the Striking Distance in the Olsen Machine.—In Table X there is given a comparison of the results obtained on the Olsen machine, using three different striking distances. The results are from connecting rods, both in the annealed and in the heat-treated condition. Comparative values obtained on the Charpy machine are also given. The results obtained with the striking distance of 0.404 in. are from two to three times the results obtained with the other distances. They are very erratic, as for instance on the heat-treated connecting rods, the results vary from 10 ft-lb. to 44 ft-lb. The results obtained on the Charpy machine for these same connecting rods vary only from 14.4 to 15.8 ft-lb. Results obtained on the Olsen machine with

TABLE VIII.—STATIC TENSION TEST RESULTS ON 0.505-IN. SPECIMEN.

NICKEL-CHROME STEEL ROD, ⅝ IN. IN DIAMETER; HEAT-TREATED; LAB. NO. 9630.
ALL VALUES ARE ENERGY ABSORBED IN FOOT POUNDS.

Specimen No.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.
1	119 800	140 800	15.0	35.4
7	92 050	105 050	19.5	63.9
13	100 750	120 300	16.5	44.5
19	110 060	135 570	19.5	52.7
25	122 300	131 330	11.6	50.1
Aver	108 600	126 610	16.4	49.3

TABLE IX.—COMPARISON OF ENERGY ABSORBED IN STATIC AND IMPACT TENSION TESTS ON SIMILAR SPECIMENS.

Static Tests.				Impact Tests.			
Specimen No	Notched Bar.	Specimen No.	Unnotched Bar.	Specimen No.	Notched Bar.	Specimen No.	Unnotched Bar.
2-A	6.4	3-A	125.7	2-B	19.4	3-B	153
8-A	9.0	9-A	120	8-B	22	9-B	168.3
14-A	11.7	15-A	115	14-B	22	15-B	152.2
20-A	13.4	21-A	94	20-B	24.8	21-B	155.9
26-A	12.4	27-A	119	26-B	20	27-B	170.9
Aver	10.6	Aver	114.7	Aver	21.6	Aver	160.0

a striking distance of 0.866 in. are nearly as uniform as the Charpy results, as also are the results obtained with a striking distance of 0.450 in.

The photographs in Fig. 12 show the fractures obtained on the Charpy machine, and on the Olsen machine with the three different striking distances. It will be seen that the Charpy and the 0.866-in. Olsen fractures show the grain structure very well. In the case of the 0.404 and 0.450-in. Olsen fractures there is so much shear that the fractures are smoothed over, so that it is impossible to tell anything about the grain structure.

TABLE X.—COMPARISON OF CHARPY WITH OLSEN MACHINE WITH DIFFERENT STRIKING DISTANCES.

NICKEL-CHROME CONNECTING RODS; SPECIMENS FROM FLAT END; NOTCH NO. 4.

Connecting Rod No.	Olsen. With Striking Distances of						Charpy.	
	0.404 in.		0.450 in.		0.866 in.			
	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.
				ANNEALED.				
8188	1	47	2	11	3	8	4	14.4
8189	4	50	1	14	2	7.5	3	14.4
8190	3	45	4	16	1	9	2	14.4
8191	2	52	3	21	4	12	1	16.9
8192	1	46	2	22	3	11	4	15.0
8193	4	48	1	26	2	11	3	16.9
Aver.		48	Aver.	18.3	Aver.	9.8	Aver.	15.4
				HEAT-TREATED.				
8194	1	44	2	12	3	8	4	15.8
8195	4	18	1	11.5	2	8	3	15.8
8196	3	42	4	14.5	1	7.5	2	15.8
8197	2	14	3	11.5	4	8	1	15.0
8198	1	10	2	7.5	3	4	4	14.4
8199	4	15	1	10.5	2	7	3	15.8
Aver.		24	Aver.	11.4	Aver.	7.1	Aver.	15.4

For the above reasons, and in order to make the striking distance of the Olsen machine compare with the standard Izod machine, it is recommended that this machine be used only with a striking distance of 0.866 in.

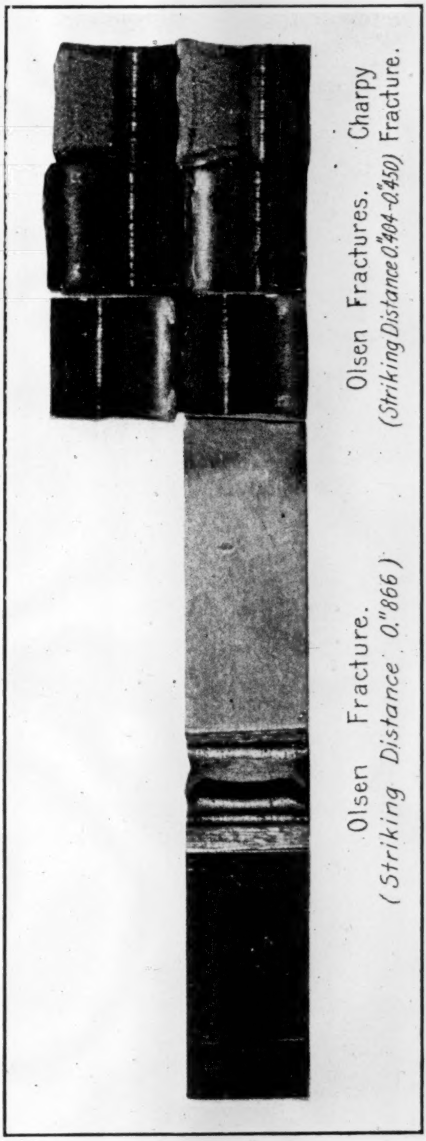

Olsen Fractures. Charpy Fracture.
(Striking Distance 0."404-0."450)
Olsen Fracture.
(Striking Distance 0."866)

FIG. 12.—Various Types of Fractures.

Comparison of Results Obtained on the Three Types of Machines.—The values obtained on the Izod and Olsen machines may be very well compared by reference to Table III. Here it is seen that the one result obtained on the Olsen machine checks very closely indeed with the four results obtained on the Izod machine. In other words, for these particular tests the Olsen machine, when set with the same striking distance as the Izod, gives practically identical results. Referring to Table VII, we are able to get a very good comparison between the Olsen, Izod and Charpy machines. Strangely enough, all three of these machines give results which, for the four types of notches tried, are very similar. The greatest exception noted is for notch No. 4 tested on the Izod machine. This gives a result markedly lower than those obtained on the other two machines. However, by referring to Table III, notch No. 4, specimen No. 23-B, it will be seen that for this particular specimen the Olsen machine checked

TABLE XI.—EFFECT OF LENGTH ABOVE NOTCH AND COMPARISON OF DRILLED WITH MILLED NOTCHES.

NICKEL-CHROME CONNECTING RODS; SPECIMENS FROM SHANK; NOTCH NO. 4.

Connecting Rod.	Condition.	Drilled Notch, Standard Length.		Drilled Notch, Length ⅛ in., greater than Standard.		Milled Notch, Standard Length.	
		Specimen No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.
				OLSEN.			
8189	Annealed	5	19	6	18	7	15.5
8192	Annealed	5	25	6	24	7	25
8197	Heat-treated	5	31.5	6	30	7	25
				IZOD.			
8191	Annealed	5	26	6	27	7	23
8196	Heat-treated	5	32	6	31.5	7	27
8198	Heat-treated	5	25	6	25.5	7	22
				CHARPY.			
				Length ⅛ in. less than Standard.			
8190	Annealed	5	26.2	6	23.4	7	21.4
8195	Heat-treated	5	43.8	6	41.7	7	30.6

[1] Striking Distance, 0.866 in.

the Izod machine very closely. The obvious conclusion, therefore, is that the low value shown in Table VII for the Izod machine is due to the low impact resistance of specimen No.

TABLE XII.—COMPARISON OF DEGREES OF FINISH.

NICKEL-CHROME CONNECTING RODS; SPECIMENS FROM BOSS; NOTCH NO. 4, DRILLED.

Connecting Rod.	Condition.	Shaped.		Milled.		Ground.	
		Specimen No.	Ft-lb.	Specimen No.	Ft-lb.	Specimen No.	Ft-lb.
OLSEN.[1]							
8188	Annealed	9	10.5	10	9.0	11	8.5
8191	Annealed	9	15.0	10	13.5	11	14.0
8194	Heat-treated	9	11.0	10	9.0	11	9.0
8197	Heat-treated	9	13.5	10	7.5	11	7.0
IZOD.							
8190	Annealed	10	12	11	12	9	14.5
8193	Annealed	10	16	11	17	9	19
8196	Heat-treated	10	13	11	12	9	18
8199	Heat-treated	10	10	11	11	9	1.4
CHARPY.							
8189	Annealed	11	11	9	15	10	12.1
8192	Annealed	11	16.5	9	18	10	29.2
8195	Annealed	11	12	9	19.5	10	12.1
8198	Annealed	11	8	9	14.5	10	9.1

[1] Striking Distance, 0.866 in.

TABLE XIII.—STATIC TENSION AND BRINELL HARDNESS RESULTS.

NICHOL-CHROME CONNECTING RODS; SPECIMENS FROM SHANK.

Connecting Rod No.	Condition.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Brinell Hardness.
8188	Annealed	54 360	99 640	19.0	42.4	174
8193	Annealed	55 420	97 75	26.5	54.9	174
8194	Heat-treated	126 060	144 780	18.0	54.8	286
8199	Heat-treated	131 450	150 340	16.0	51.8	277

23-B. Table X has already been referred to. This shows that on the connecting rods tested, the Olsen machine with a striking distance of 0.866 in. gives results very much lower than the Charpy machine.

TABLE XIV.—COMPARISON OF IMPACT AND TENSILE PROPERTIES.

Specimen		Nichol-Chrome ⅝-in. Rod, Heat-treated.	Nichol-Chrome Connecting Rods.[2]	
			Annealed.	Heat treated.
Yield Point, lb. per sq. in		108 600	54 800	128 700
Tensile Strength, lb. per sq. in		126 610	98 000	147 540
Elongation in 2 in., per cent		16.4	22.8	17.0
Reduction of Area, per cent		49.3	48.7	53.4
Brinell Hardness		269	174	284
Impact, Ft-lb. Notch No 4	Olsen.[1]	24.0	22	31.5
	Izod.	17.9	26	28.5
	Charpy.	24.1	26.2	43.8

[1] Striking Distance, 0.866 in.

[2] Specimens taken from shank of the rods.

In Table VI is given a comparison of results obtained on the Olsen, Izod and Charpy machines for unnotched specimens. It will be seen that for these specimens the results do not agree at all. The results on the section 0.394 by 0.197 in. were obtained first, and since these values were so much higher than those obtained on notched bars, it was thought that the difference in the results of the three machines was due to the different range of scale reading. Therefore, the smaller specimens were made up and tested, and although these results are in the usual range of notched bar values, they do not agree at all. By comparing the ratio of the values obtained on the different machines, it was found that they vary in somewhere near the same proportion as the square of the velocity of the center of gravity of the pendulum at the instant of breaking the specimen. These ratios are given below:

SECTION.	IZOD.	OLSEN.	CHARPY.
0.394 by 0.197 in	1	1.476	2.045
0.197 by 0.197 in	1	1.457	2.100
V^2	1	1.53	2.39

Comparison of Energy Absorbed in Static and Charpy Tensile Tests.—Referring to Table IX, it will be noted that for the notched bar, there is required about twice the amount of energy to fracture it in the impact test as is required in the static test. For the unnotched bar, the impact test requires about 1.4 times the amount of energy as the static test.

A notched bar in the impact test requires just one-eighth the energy required to break an unnotched bar of the same breaking area. In the static test, the notched bar requires about one-twelfth of the amount required by the unnotched bar.

Comparison of Types of Notches.—Table IV gives the values obtained on the Olsen impact machine for the four different types of notches. The effect of the radius at the bottom of the notch is very strikingly shown in this table. The rounded "V" notch with the breaking area of 80 sq. mm. requires about the same energy to fracture as the cylindrical notch with a breaking area of 50 sq. mm. With a "V" notch having a sharp bottom, there is required about 7 ft-lb. less than for a "V" notch with a radius at the bottom of 0.01 in. The same comparison may be made for the Izod machine (Table III) and for the Charpy machine (Table V).

Effect of Length of Specimen.—By comparing the results obtained on specimens Nos. 5 and 6, Table XI, it will be seen that making the length of the specimen above the notch $\frac{1}{8}$ in. greater in the case of the Izod and Olsen machines has practically no effect on the results obtained. Making the specimen $\frac{1}{8}$ in. shorter in the case of the Charpy machine seems to lower somewhat the total amount of energy absorbed. This amount is very small, however, so it may be said that in the case of all three machines it will not be necessary to hold the length of the specimen to a closer tolerance than ±0.05 in., provided that in the case of the Charpy machine it is not so long as to cause the specimen to rub on the sides of the anvil in breaking.

Effect of Degree of Finish.—In Table XII are given the results obtained on the three types of machines on specimens prepared in three different ways. From these results it is concluded that if the specimen is reasonably well finished, the degree of finish has no effect; that is, it most decidedly is not necessary to grind the specimens. Specimen No. 9 in every case showed a higher impact resistance than any of the others. Referring to the sketch showing the location of these specimens, Fig. 10, it will be seen that specimen No. 9 is located at the end of the shank of the rod. Evidently this location gives a higher impact resistance than locations Nos. 10 and 11.

Comparison of Drilled and Milled Notches.—Referring again to Table XI and comparing specimens Nos. 5 and 7, it will be seen that in every case specimen No. 7 gave a lower impact resistance than No. 5. The notch was drilled in the case of No. 5, and milled in the case of No. 7. It may be concluded, therefore, that the milled notch gives results some 3 to 4 ft-lb. lower than the drilled notch.

Comparison of Impact and Tensile Properties.—Table XIV gives a summary of the tensile properties, Brinell hardness, and impact results for the two lots of material discussed in this paper. The reason for the low value of 17.9 ft-lb. on the Izod machine obtained in the case of the $\frac{5}{8}$-in. rod has already been explained.

CONCLUSIONS AND RECOMMENDATIONS.

1. The striking distance of the Olsen machine should be fixed at 0.866 in. (22 mm.) to compare with the present Izod standard, which should be maintained. The span of the Charpy machine should be fixed at 40 mm. (1.575 in.) to compare with the French standard.

2. No absolute means of converting the results from one machine into those of another is possible except for very special cases. Comparison of results obtained on the three different types of machines should be made only with the greatest care.

3. A standard square specimen, 10 by 10 mm., should be adhered to. The writer has discussed the comparative costs of preparing square and round specimens with a number of well informed machine shop superintendents, and all have agreed that by properly rigging up for quantity production, a square specimen can be prepared by a pair of straddle mills just as economically as the round. It is by far the most desirable from the point of view of testing. A tolerance of ±0.0015 in. should be maintained on the cross-section.

4. A standard length of specimen for each machine should be adopted. The lengths used in these experiments are recommended for the reasons previously stated. These should be held to a tolerance of ±0.05 in.

5. One type of notch should be adopted for all three machines. From the point of view of duplicating the results in different plants, the writer recommends a notch 5 mm. deep drilled with a 2 mm. diameter drill in a jig similar to the one discussed. The notch should be completed with a saw cut.

6. Jigs should be used in setting the specimens in the machines.

7. Each machine should be carefully calibrated by the method described.

8. If the preceding recommendations are followed there is no reason why the results obtained by one manufacturer cannot be duplicated by another, provided they are made on the same type of machine.

9. The notched bar impact test is satisfactory, and necessary as a plant control proposition.

DISCUSSION.

Mr. Miller. MR. C. P. MILLER (*by letter*).—Mr. Dix's paper is one more proof of the growing importance of the impact test and of its general recognition as an effective means of determining resistance to shock. It also shows that with due care consistent results can be obtained with a given type of machine. In view of these facts, I wish to make the following suggestion.

For many years we have had the so-called merit number obtained by multiplying the maximum strength by the elongation. The value thus determined is a rough approximation of the work done in breaking a specimen. The use of this number to represent the merit of the steel is open to several objections. In the first place, it does not distinguish between two steels with the same maximum strength but with the elastic limit of one perhaps 25 per cent higher than the other. As the elastic limit controls the working strength it is obvious that the first steel is discriminated against. In the second place, tests, especially on alloy steel, have shown that the elongation or ductility is not as important a quality as the resistance to shock which is shown by the impact test and possibly by the reduction of area. In our laboratory we made several thousand tests on each of two lots of chrome-nickel steel which had the same tensile strength and elongation. The impact strength of one lot, however, ran about three times as high as the other, and it is plain that there was in this case an important difference in the quality of the two steels which was not uncovered by the elongation.

For that reason, I propose a new merit number to be formed by the product of the elastic limit and a function of the impact strength, the function used and the type of machine to be determined later. In this way, I believe, a number would be obtained which would actually show the respective merits of various steels in a practical way.

DEVELOPMENT OF BRINELL HARDNESS TESTS ON THIN BRASS SHEET.

By S. L. Goodale and R. M. Banks.

SUMMARY.

The development of a small Brinell machine for testing thin sheet is described, using a ball $\frac{1}{16}$ in. in diameter and an applied load of 15 kg. The Brinell test with this machine responds readily to any appreciable change in hardness of the brass, and shows a fairly close correspondence with results of tests with the standard machine.

Two slightly different types of small Brinell machine are described, both considered to be excellent and practical machines.

The importance of a method of operating Brinell machines which is free from inertia effects is emphasized.

The small Brinell machine in connection with microscopic examination is believed to furnish means for control of manufacturing operations and quality of finished articles of brass.

DEVELOPMENT OF BRINELL HARDNESS TESTS ON THIN BRASS SHEET.

By S. L. Goodale and R. M. Banks.

Early in the summer of 1918 a request to develop a satisfactory method of testing hardness of thin brass sheet was brought to the Control Laboratory of the Inspection Division, Ordnance Department, U. S. Army. The particular object of the investigation was to develop more satisfactory methods for determination of the hardness of brass in the cartridge cases used in the .30 caliber rifle and machine gun.

The investigation divided itself naturally into three parts: first, to determine what would be a satisfactory method and machine for the hardness testing; second, to develop the necessary details of the test chosen; and, third, to determine what constituted the proper physical quality of hardness for the cartridge cases.

In regard to choice of test, the Laboratory was rather limited by the stress of war conditions, and the necessity of developing quickly some test which would serve the purpose. Inasmuch as the British had developed a small Brinell machine which was reported to be satisfactory for similar work, this test was chosen as the standard very early in our investigations, and our energy thereafter was devoted mainly to it. The test had to be worked up from the beginning, as we had few details of the British work at first.

The present paper describes the development of the details of practice found necessary for a Brinell test on thin sheet brass, the Brinell machines developed for the test, and some further results. For a test so well known as the Brinell, it was very remarkable how many little details had to be worked out to secure satisfactory results. The application of our findings to the special problem of cartridge manufacture is not dwelt upon here, as that is of interest mainly to the cartridge manufacturers.

It may be mentioned here that very promising results were secured from the limited work done on certain other tests, and it is hoped that it may be possible to present these in a later paper.

A very large amount of work was conducted to adapt the standard Brinell test to the measurement of hardness of thin sheet brass. In fact, this "Baby Brinell" is the only test of all those considered that was thoroughly developed at the Control Laboratory. It is believed that the technique of this test was brought to a satisfactory point of development, and that the test and machines as developed are very accurate and reliable. For this reason it is hoped that the following rather full description of the steps in the development will be of general interest and use.

The standard Brinell Machine using a 10-mm. ball under an applied load for brass of 500 kg. gives too deep an impression to have the full effect taken up in thin sheet, and in testing thin sheet the influence of the backing or support for the sheet masks the effect of the hardness of the sheet itself so much that reliable results are impossible to secure with the large machine. It was necessary to construct a Brinell Machine using a very much smaller ball and load than standard practice demands, in order to have the effect of the test entirely taken up within the small thickness of metal actually under test. The sheet under the loaded ball must be in perfect contact with the hard anvil, so that none of the deformation effect will be left to be taken up by the anvil or by bending the sheet into the form of a conical cup with the ball impression at the apex thereof, — at least, when considering a small sized ball from 1 to 2 mm. in diameter and sheets of about 0.01 in. in thickness. The minimum thickness of sheet which can be tested under this condition is considered to be a sheet having a thickness of about four or five times the depth of the impression produced by the ball.

The size of ball chosen at the Control Laboratory, $\frac{1}{16}$ in. in diameter, was the smallest ball quickly available from any stock, although millimeter size balls would have been preferred, because of their use in the British tests. After the experimenting had proceeded to a considerable extent it was believed better to continue the work with the above mentioned ball size rather than to risk the delay of changing to 1-mm. balls which would have to be specially made. Such a change might have extended the time considerably before valuable results would be available. Our experiments with the small Brinell Machine now indicate clearly that the results of testing will be very nearly the same with different size balls and suitably proportionate loads within pretty wide limits; and the relationship can be determined to compare conveniently the results of testing with the large size Brinell Machine using a 10-mm. ball and a 500-kg. load. In view of the small size of ball and weight adopted for this testing, and the more refined machine made necessary thereby, it was deemed advisable to use a dead weight type of machine, so that no friction of levers or other parts could alter the actual load applied to the ball.

TABLE I.—BRINELL TESTS ON ANNEALED BRASS SHEETS OF VARIOUS THICKNESS.

Anneal.	Sample No.	Approximate Thickness, in.			
		0.007–0.012	0.013–0.018	0.016–0.023	0.030–0.035
550° C.	1	57	57	57	56
	2	61	54	62	62
	3	51	55	58	53
650° C.	4	51	48	51	47
750° C.	5	49	49	40	38
	6	43	45	..	40

NOTE.—The above figures should not be considered as giving comparative figures on hardness due to different annealing temperatures. Each line of figures was taken from one experiment and shows reasonably good agreement in Brinell number on brass of differing thickness. The discrepancies, such as the number 54 for sample No. 2, are mainly due to local differences in hardness of the brass.

From an investigation at Woolwich Arsenal, England, reported in 1909 at the Fifth Congress of the International Association for Testing Materials, Mr. Harold Moore concluded that when the ratio of depth of impression to thickness of sheet is less than 1 to 3, the effect of thickness of test piece on diameter of impression is not more than 1.5 per cent, corresponding to about 3 per cent on hardness number. The effect of thickness of sheet on the test grows less and less with thicker and thicker sheet, and Mr. Moore further concluded that at a ratio of 1 to 7, and when there is perfect contact between test piece and anvil, the thickness of sheet tested has no influence on the test.

Fully annealed brass runs about 40 Brinell, but comparatively few finished brass parts as used would run softer than 70 Brinell, which gives with our machine an angle of impression of about 19 deg. 30 min., a theoretical depth of impression of about 0.045 mm., and a ratio of depth of impression to thickness of brass tested of 1 to 5.65 down to 1 to 6 for the 0.01-in. brass sheet, the thinnest we regularly tested.

In order to test thoroughly whether our results can be counted on as being free from effect of thinness of sheet tested, a number of cartridge cases were annealed at various temperatures and the Brinell hardness measured at points varying considerably in thickness. Results of some characteristic figures from these tests are given in Table I. Harder brass will show less influence from thickness than this soft material.

These figures, considered in the light of Mr. Moore's results and with the precautions employed to prevent bending or denting of the sheet, indicate very strongly that the sheet tested was thick enough to absorb all of the deformation produced by the ball.

The ordinary method of figuring the Brinell number was used for tests on flat sheets; namely, load on ball divided by spherical area of impression. For our work it was desired to make a considerable proportion of our tests on the cylindrical surface of the cartridge cases, partly to avoid having to file off a flat space and thus leave a thinner piece for test, and partly for other reasons. A relatively shallow ball impression on a cylindrical surface, where the ball diameter is only a small fraction of the cylinder diameter, shows contact area of a peculiar shape. The area of this impression is closely approximated by the formula:

$$\frac{\pi D}{2}\left(D-\sqrt{D^2-(C+T)^2}\right),$$

in which D is the ball diameter, C is one-half the short and T one-half the long diameter of the impression in the cylindrical surface. The above is seen to be a slight modification of the usual formula:

$$\frac{\pi D}{2}\left(D-\sqrt{D^2-d^2}\right)$$

C in the preceding formula is obtained from the following relationship, wherein *R* is the radius of the cylinder, and *r* the radius of the ball:

$$C=\sqrt{R^2-\frac{[(R+\sqrt{r^2-T^2})^2+R^2-r^2]^2}{4(R+\sqrt{r^2-T^2})^2}}$$

This modification of the usual formula is here inserted as it may assist in other cases of testing on cylindrical surfaces.

Tables were prepared giving Brinell numbers both for flat surfaces and for cylinders. The tables have been arranged in a convenient form similar to the usual arrangement of logarithmic tables.

TABLE II.—BRINELL TESTS WITH SMALL MACHINES (NOS. 1 AND 2) USING DIFFERENT WEIGHTS.

Sample No.	Weight, kg.					
	5	10		15		25
		A	B	A	B	
7	..	....	....	....	124	125
8	..	....	....	....	66	67
9	..	83.5	85	83.5	86	..
10	..	103.5	106.75	109.25	117.5	..
11	..	44	46	50	53	..
		No. 1.	No. 2.	No. 1.	No. 2.	
12	..	78	90	81	84	..
13	..	93	106	101	106	..
14	..	....	54.1	....	56.5	..
15	..	....	53.8	....	55.7	..
16	48	....	49	....	54	..
17	66	....	55	....	62	..
18	66	....	55	....	65	..
19	68	....	53	....	69	..
20	62	....	60	....	70	..
21	50	....	46	....	45	..
22	58	....	61	....	85	..

A and B—different operators.

Some characteristic figures showing how the Brinell numbers compared on certain samples when different weights were used are given in Table II. Two different small machines were used on these tests, designated Nos. 1 and 2. Where both A and B figures are given, the A figure is by one operator, B by another. Two independent operators usually agreed very closely in their work, and the divergencies in this table are probably due more to actual differences in the hardness of the specimen than to differences personal to the operator.

In Table III is given a comparison of our small machine with the standard hydraulic machine using 500 kg. on a 10-mm. ball. The difference between the figures with the standard machine and those with the small machine are of much the same order as the differences found from different methods of operating the latter. The ordinary method of operating the standard machine corresponds with the first method used with the small machine, the method which was afterwards discarded. This manner of method of operation is discussed later.

TABLE III.—COMPARISON OF BRINELL HARDNESS TESTS ON SMALL MACHINE AND STANDARD HYDRAULIC MACHINE.

Sample No.	Small Machine.	Standard Machine.
23	135	116
24	130	121
25	123	114
26	121	119
27	119	112
28	103	100
29	101	96
30 (Cupro-nickel)	84.5	74
31 " "	83.8	70
32 " "	82.7	66
33 " "	71.2	60
34	71.8	55
35	66.6	62
36	66.4	63
37	66.2	54
38 (Cupro-nickel)	62.7	45
39 " "	57.7	44
40	54	49

NOTE.—The above figures with the small machine were obtained with a 15-kg. load, using the second method of operation described below.

The first experiments were made with a simple apparatus shown in Figs. 1 and 2, mounted over the platform of a sensitive Troemner laboratory scale. The advantage of this rig was that any desired weight could easily be applied to determine what was most suitable for a ball of any given size. With this machine, which we shall call No. 1, tests were run to find the best weight for use with the $\frac{1}{16}$-in. ball. A range of weights from 5 up to 25 kg. was tested. The 5-kg. weight did not seem to develop as much difference between the various hardnesses of brass as was developed by a heavier weight. Insufficient penetration of the ball produces shallow impressions whose outlines are not clearly enough defined to insure accurate measurement. The 25-kg. weight had too much of a tendency to cup the thinner sheet, and made the impressions too deep for the thin sheet which had to be tested. These faults were still somewhat in evidence with 20 kg.

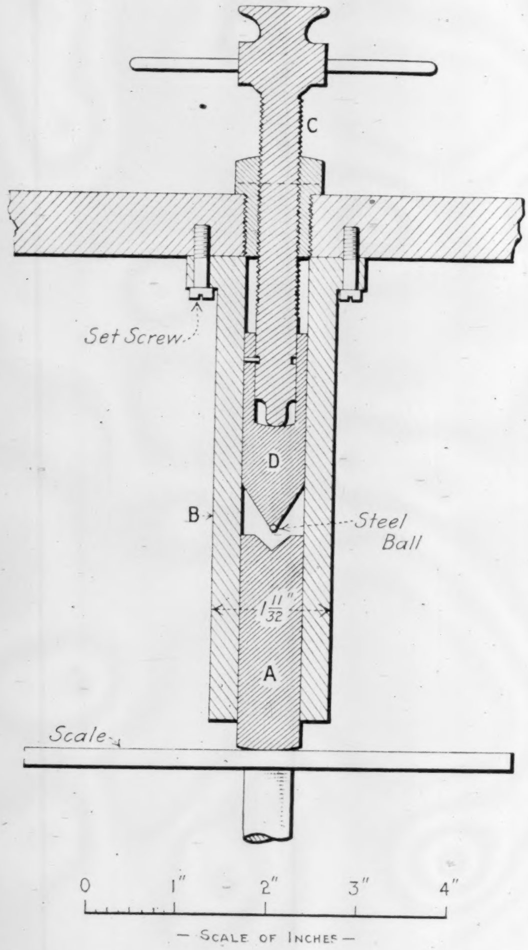

C
Set Screw
D
B
Steel Ball
1 11/32"
A
Scale
0
1"
2"
3"
4"
— SCALE OF INCHES —

FIG. 1.—Diagram of Small Brinell Machine No. 1.

It was difficult to decide this matter closely on technical grounds; and finally 15 kg. was chosen more or less arbitrarily, and continued as it gave good results.

In the operation of this machine, the test piece was placed on the anvil and the ball run down against it by means of the screw in the top plate of the yoke until a pressure sufficient to raise the beam of the balance was exerted. We may call this method 1. This method with the screw-down device resulted in intermittent increases of pressure, which it was feared might lead to unreliable results. There is also a chance of greater relative side motion between the ball and test piece, resulting in distorted and damaged impressions, when both ball and test piece are mounted on moving supports than when the ball only is on a moving plunger and the test piece on a fixed anvil. In particular, it is necessary to avoid any "side swipe" of the ball against test piece when the ball is leaving the impression after the application of load. After a considerable amount of testing with this device the levers shown at the left in Fig. 2 were added so that instead of screwing the ball down against the test piece and thereby raising the lever arm of the scales, the lever arm could gradually be lowered, thus forcing the test piece under a given

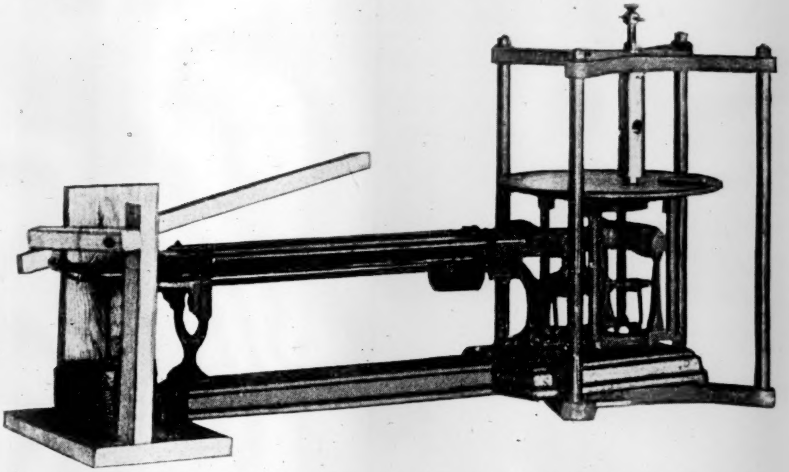


FIG. 2.—Small Brinell Machine No. 1. Levers at left added to operate the machine by "Method 2."

load in contact with the ball, the ball remaining in a fixed position. This we may call method 2.

A rather surprising difference in results developed between these two methods of applying the load. The second method of operation gave impressions of smaller size for the same brass. ball and weight. The important point we found was that it gave more consistent results than the first method, and because of this fact the standard laboratory machine was built to be operated according to the second method, that is, in such a way that the ball would be forced down gradually into the brass surface by the 15-kg. weight applied.

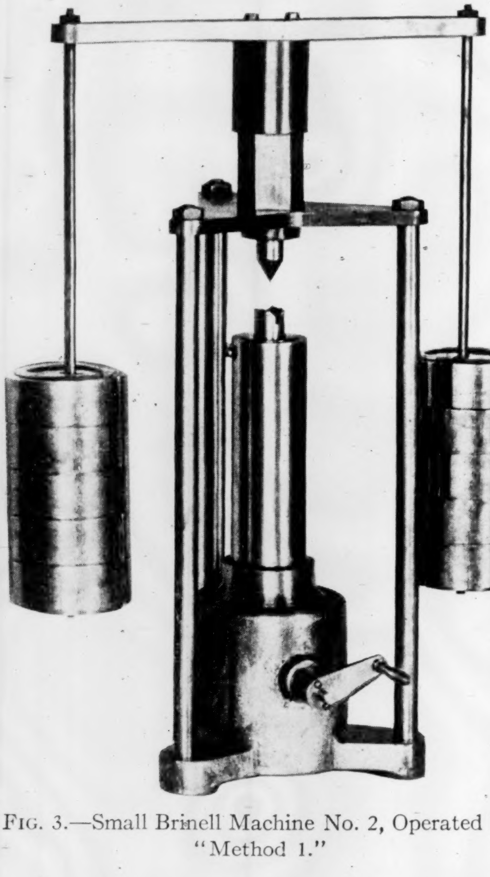


FIG. 3.—Small Brinell Machine No. 2, Operated by "Method 1."

Meanwhile a second machine (designated machine No. 2) was built of an entirely new design to secure rapidity and ease of operation, and if possible, greater accuracy. This was a dead weight machine, and is shown in Fig. 3. The Brinell ball is held magnetically at the bottom end of a steel plunger on the top of which swings a yoke carrying the load. This plunger originally was carried by means of a collar on a heavy coiled steel spring capable of carrying a 15-kg. load, with a compression of about 2 mm.

It might be mentioned here that this magnetic holding of the ball if relied on alone may give some trouble, as the ball tends to hang at the extreme edge of the ring about the conical seat in which it is desired to hold it; and it is necessary to make the ball seat fairly tight in the conical depression, so that the hold is partly by mechanical friction and only partly magnetic. To overcome the trouble with this magnet holder another was designed in which the ball seat was made of austenitic steel, or other hard non-magnetic metal, and a small permanent magnet with one or both poles just back of the ball seat so placed as to draw the ball into the seat. The magnetic hold would be of no service where it is desired to test iron or steel.

The anvil, centered vertically under the ball, is raised or lowered by a crank operating through bevel and screw gear, inside the central standard of the machine. The test piece is placed on the anvil and forced up against the ball, raising the ball plunger free of the spring until the test piece carries the full load on the ball. It will be seen that this method of operation corresponds to the first method of operating the earlier machine, and the results agree fairly well therewith. Some irregularity occurred in operation, because of which the spring was removed; the new results were about the same as with the spring, but were rather more regular.

Next the method of operating this machine by a plan similar to the second method with the first machine was investigated. For this purpose the machine was partly rebuilt, as shown in Fig. 4, so that the ball carrying the load could be slowly lowered against the test piece which rested on a fixed table or anvil. The lower cross-bar of the small yoke shown in Fig. 4 is fastened rigidly to the table plunger and thus raised or lowered by the crank and gears. The upper cross-bar of this yoke carries the ball plunger and weights, raising or lowering them as required. The table is formed by a cap fitted over the central column and slotted at the sides, and having the anvil mounted on top. This method of operating this machine gave results agreeing quite closely with those of the second method of operating the first machine.

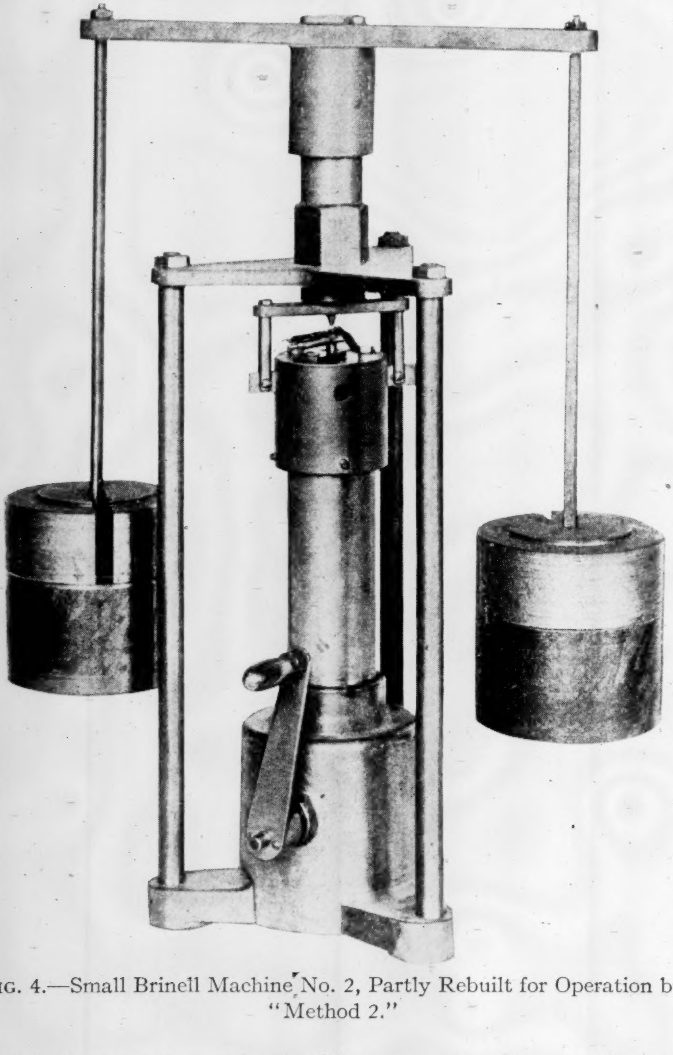


FIG. 4.—Small Brinell Machine No. 2, Partly Rebuilt for Operation by "Method 2."

Some interesting points developed in connection with using this machine with and without spring, and also in connection with the mechanisms tried in connection with altering the type of machine from the first to the second method of operation. The spring was originally placed in this machine to avoid any inertia effects which might arise from rapid operation. When it was used the ball plunger and weights were raised in contact with the test piece some 2 mm. or more, and the anvil carrying the test piece was elevated this amount plus the depth of impression. When the spring was removed this travel was cut down to a few thousandths of an inch more than the depth of impression, that is, just enought to insure lifting the ball plunger from its rest to its load position. The lessening of this travel accounts for the more uniform results obtained without the spring.

In connection with mechanisms for lowering the ball plunger onto the test piece,—that is, for operating the machine by the second method,—we tried at first a light wire fastened centrally to the top of the plunger and running over a small shaft turned by crank and worm gear so that the motion of lowering could be continuous. This method of lifting did not give as clean edges to the impressions as we secured after adopting the device described, which is similar to that used in the later machines. We were not able to find any wire or other suspension that was satisfactory for this form of lift; everything we tried was either too light for the work or affected appreciably the weight applied. It was impossible also to get the lift properly centered, and we found that the plunger is held more steadily in position in its guiding cylinder when the lifting is done by a frame bearing against the collar near the lower end of the ball plunger. In order to avoid noticeable friction there must be some play between the plunger and its guiding cylinder, which even though something less than 0.0005 in. is an appreciable figure considering that the Brinell impressions are measured to the nearest 0.001 mm.

Five pieces of brass were cut from a strip and tested according to the second method of operating the second machine with the following results, each figure being the average of diameter in thousandths of a millimeter of 12 impressions:

393, 391, 391, 390, 391..............Average, 391.2.

The first machine operated by the first method of operation, gave 441, and by the second method of operation, 382, in comparison with the average of 391.2 given above.

The second machine, with our original method of operation, gave 415, and when the spring was removed but the machine operated by the same method, the result was 422.

The Brinell readings from which these results are quoted are given in Table IV, to illustrate particularly the greater uniformity of results secured by the method of operation adopted.

Extreme variation by method 1 is 0.041 mm., by method 2 is 0.019 mm., while with method 2 there is better approximation of most figures to the average.

TABLE IV.—BRINELL TESTS ON MACHINES NOS. 1 AND 2, BY TWO METHODS.

Machine No.	1	1	2	2	2	2	2	2	2	2
Method No.	1	2	1 *s*	1	2 *s*	2	2	2	2	2
Diameter of Impression, expressed in 0.001 mm.	449	392	412	420	389	392	395	386	392	392
	441	385	408	423	388	394	400	390	390	392
	441	380	416	412	386	394	396	390	391	391
	433	388	420	418	389	394	390	388	390	391
	444	388	413	414	387	393	388	391	390	396
	442	......	414	......	381	393	392	391	386	392
	442	377	414	418	381	393	390	394	394	392
	438	381	412	428	...	392	390	398	386	390
	444	370	419	427	384	392	384	391	393	386
	440	380	420	432	382	390	386	388	390	388
	440	376	418	436	384	398	394	...	392	388
	442	376	414	419	390	393	388	390	390	392
Average	441	382	415	422	386	393	391	391	390	391
Average Brinell Numbers	96.3	129	109	105	126	122	123	123	124	123

s indicates spring used.

It will be seen that considerably larger impressions were obtained by the original method in which the ball carrying the weight is raised from a state of rest by means of the test piece being forced up against it. It will also be noted that the results from the second method of operating are more regular, and because of these, more uniform results secured when the machines were operated by lowering the ball slowly against the test piece until it came to rest, this method of operation was adopted as our standard.

It is believed that this practice results in greater uniformity of test and, therefore, more reliable results than usually secured with the standard Brinell machine. The effect of the personal equation of the operator is very slight in our method of operating, whereas with the ordinary method of operating the standard machine it is apt to be considerable.

This matter of method of applying load is of considerable importance where accurate results from Brinell testing are desired, and a few words in explanation may be advisable. The difference referred to here is that between permitting the weighted ball to descend slowly against the test piece until it comes to rest and on the other hand raising the test piece slowly until the weighted ball is lifted from rest. In the first case the moving load is gradually retarded as the ball is forced deeper and deeper into the metal until it finally is stopped. In the second case, while the load is being gradually transferred to the test piece from its former support the ball is gradually being forced into the test piece by the applied load, but is not actually lifted until the impresson is nearly as deep as the dead weight will make it. The momentum slowing down the weight when it is permitted to descend slowly against the test piece is taken up in the time interval between the first contact of ball against test piece and completed impression. The motions involved are so small and may be made so slow that it is easy to overlook the fact that small as the motion of the weight is in the case of the hydraulic machine and the first method of using our small machine, the time during which acceleration takes place is almost instantaneous, which makes the actual acceleration at a very considerable rate and the force to produce this acceleration appreciable.

There must be a "kick" from the lifting of these weights from rest, after most of the impression has been formed. That is to say, although the application of the load is slow there comes a point at the instant of starting the weight from rest when the pressure due to starting to lift the load must be higher than the static pressure of the same load at rest.

It will be noted that the discarded method corresponds somewhat to the regular method of operating the standard Brinell machine with control weights. Tests at the Control Laboratory show in the case of an American-made machine that the control weights refused to lift until the gage indicated a pressure of nearly 3100 kg. A similar test with Aktiebolag Alpha Swedish machine showed that the control weights with this machine lifted when the gage reading was about 3040 kg.

The results obtained at the Control Laboratory correspond very clearly with this idea, inasmuch as the Brinell practice where weighted ball was lifted from rest invariably gave deeper impressions in the brass than the other practice where the weighted ball was slowly lowered against the test. Other previous work also has indicated that the maximum weight applied in the Brinell test is of more importance than the duration of the application of the weight. Furthermore, it will be noted that the motion with the new practice is continuous until full load is applied, whereas with the hydraulic type as now used the increase of pressure is intermittent. In the rest periods between successive increments of pressure the metal sets in a hardened condition, so that the final test is made on metal hardened by work in a sensibly different way from the hardening due to a continuous flow of metal of the same total extent. It should be relatively easy so to design an hydraulic type of Brinell machine as to secure a constantly instead of intermittently increasing pressure on the ball, although such a machine would doubtless be slightly more expensive than the present usual type.

In regard to measuring the impression, two methods are theoretically possible, namely, the measurement of depth of impression and the measurement of diameter of impression. Of these methods the one adopted was the measurement of diameter of impression and for this measurement the standard equipment chosen was a metallurgical microscope with 16-mm. objective and a filar micrometer type of eye-piece, the tube length being such as to give direct reading ratio between the plane of the sheet and the scale of the micrometer eye-piece.

At the edge of the impression there may be zero deformation or there may be a depression formed or a ridge raised. In most of the tests with the Baby Brinell Machine, so far, this deformation has been so very slight as not to complicate the reading of the diameter of impressions, the edges of which, when properly lighted by the vertical illuminator, show very sharp under the microscope. It is possible for different operators to agree in reading the diameters of impressions to about 0.001 or 0.002 mm. The form of micrometer adopted is preferred to the fixed scale eye-piece micrometer. A very good stepped micrometer was the best found of the latter type and was tried out, but found to be difficult to read and very tiring to the eye. A measuring microscope made by Gaertner & Co. was also tried, and can be used with fair satisfaction. This instrument is better where the individual measurement is over a distance of several millimeters as in the regular large Brinell machine; but the filar type eye-piece micrometer is much superior for the small measurements involved with the Baby Brinell machine. It is essential to have the microscope equipped with a good mechanical stage for rapid and exact spotting of impressions for reading.

During the development of these two machines the detail of preparation of surface for test was found to be very important. The ideal preparation seems to be a polish about the same as is required for microscopic examination of structure. The surface should be free from scratches and irregularities. It is first buffed with a Tripoli compound sufficiently abrasive to remove coarse scratches and indentations. This is followed by a final buffing with jeweler's rouge. The slight dragging from the surface with this preparation, which would be bad for microscopic examination, has no appreciable effect on results in this work.

In the course of testing with machines Nos. 1 and 2 the question was repeatedly raised as to the effect of friction between the plunger carrying the ball and the guiding cylinder in which this plunger slides. It was feared that this friction might operate to diminish the actual total weight applied to the ball in the test, because of there being enough friction to sustain actually a sensible portion of the load. The surest way to determine whether this was the case or not was to construct a machine which should be free from such a defect. Accordingly machine No. 3 was constructed, following somewhat the design of a machine built in England some time earlier, but in regard to which we had not received details until after our earlier machines had been built.

Before designing this machine the matter of rate of appli-

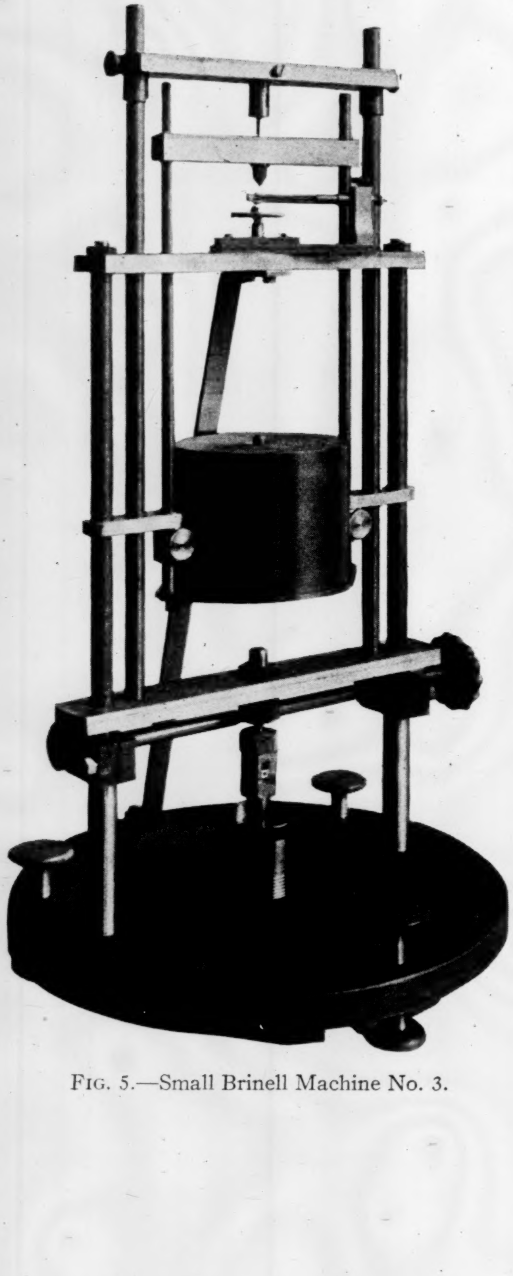


FIG. 5.—Small Brinell Machine No. 3.

cation of the load had received considerable attention, and we had standardized our practice by having the operator watch a long pendulum and count time in order to make the application of the load practically uniform in all tests. We did not actually determine what would be the effect of widely different rates of application of load, but we did make a considerable number of experiments on this point. These tests showed that the rate of applying load could vary within reasonable limits for practical operation without serious effects on the uniformity of tests. At this time it was suggested that we apply a dash pot to control the rate of application of the load by having a piston force oil through a needle valve, the opening in which could be regulated. A wide range of adjustment of rate was thus readily secured, and this device reduced to a minimum the personal equation of the operator making the tests.

Machine No. 3, as shown in Fig. 5, consists of three frames, the outside one being rigidly mounted on a heavy circular base and forming the support of the operating parts. The inner frame carries the test ball and load and weighs altogether 15 kg. This is raised or lowered by the middle frame on which it is hung by a centering link at the top with the point of support accurately over the ball. The anvil or table of this machine is supported by the outer frame. The uprights of the lifting frame slide easily in bearings in the fixed frame, and the inner frame hangs entirely free when a test is being made, its total weight resting on the ball and pressing the ball into the surface under test. Wide swinging of this inner frame may be prevented by guides which, however, are open enough to avoid any friction. These guides, if used, must be at the right level on the frame, a little above the center of gravity of the weight.

In actual routine operation for ordinary work, a number of points developed wherein this design may be, perhaps, somewhat less convenient in operation than a machine like No. 2 where the ball is carried on a guided cylindrical plunger. Careful and prolonged tests with both machines showed that the friction effects feared were negligible or nearly so in a well-built machine kept properly cleaned. It is, however, necessary to test occasionally to see that the plunger is sliding freely. As machine No. 2, after having been rebuilt for operation by our

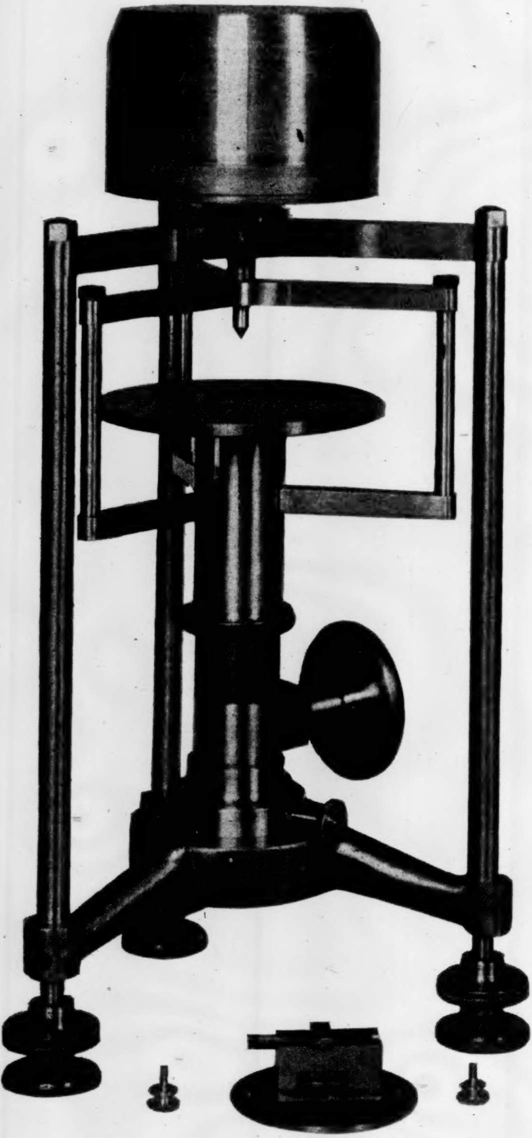


FIG. 6.—Small Brinell Machine No. 4.

second method, was found to be somewhat inconvenient in use, and as an additional machine was desired, we accordingly designed machine No. 4, which we have recommended for general work.

COMPARISON OF MACHINES NOS. 3 AND 4.

Thickness of Sample, in.	MACHINE No. 3. Average of 8 Tests.	MACHINE No. 4. Average of 12 Tests.
0.0318	103.7	105.3

Machine No. 4, as shown in Fig. 6, consists of a light rigid frame of three uprights carrying an upper plate on which is mounted the cylindrical guide for the ball plunger. In the central column is a dash pot with piston and needle valve to control the rate of drop of the lifting frame, which is the three-post inner frame about 6 in. high. In addition to insuring uniformity of speed of application of the load and consequent uniformity of inertia effects, the application of the dash pot simplifies the operation of the machine and considerably reduces the time and labor involved. This proved an important factor in our work as it was frequently necessary to make as many as a thousand impressions a day. The table of the machine is a circular plate mounted on the central column so as to be rigid and yet fairly readily adjusted for height when testing pieces of different thicknesses. This machine is operated by the small hand wheel acting through a cam inside the central column on the base of the lifting frame. The various anvils are mounted on the table, being located thereon so as to be readily centered, and fastened by convenient thumb screws. Since this photograph

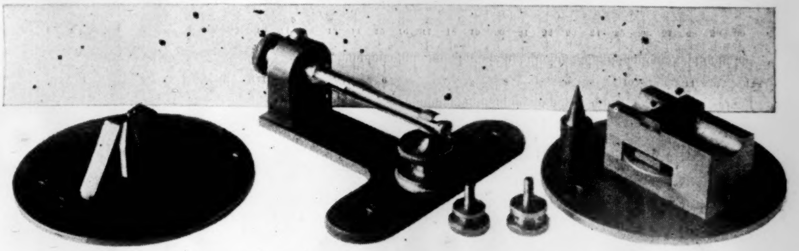
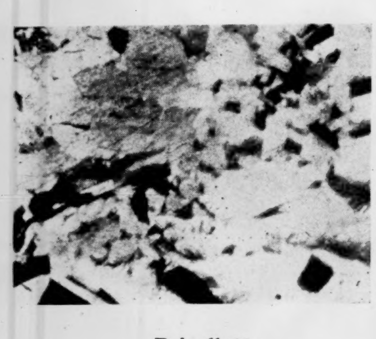
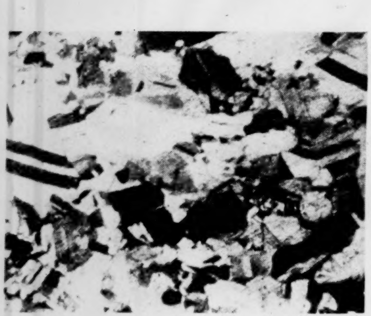


FIG. 7.—Three Anvils Used in Special Work.

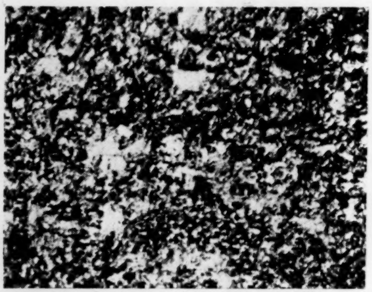


Brinell 69.

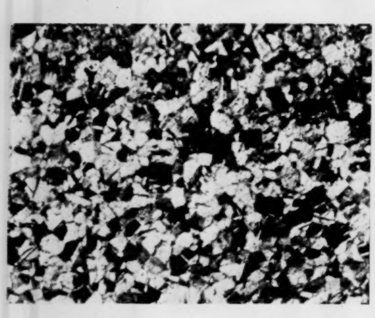
Brinell 100.



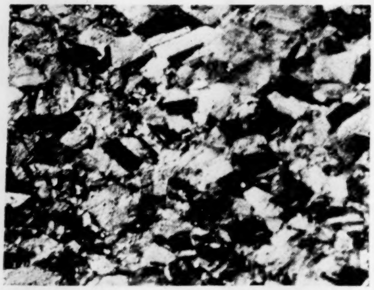
Brinell 74.



Brinell 109.

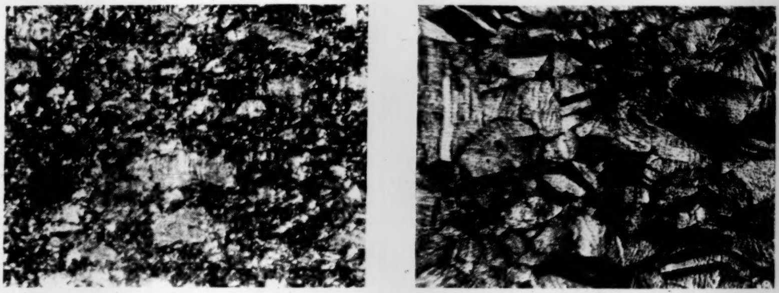


Brinell 90.

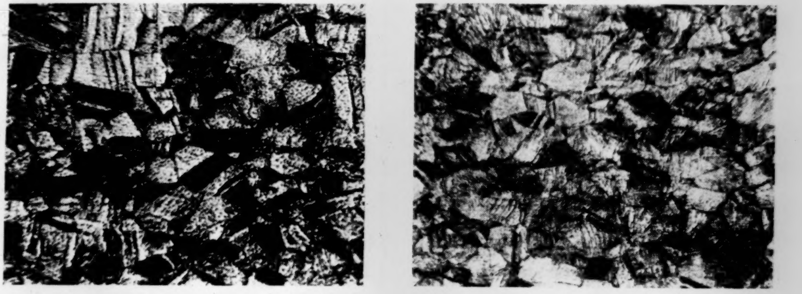


Brinell 120.

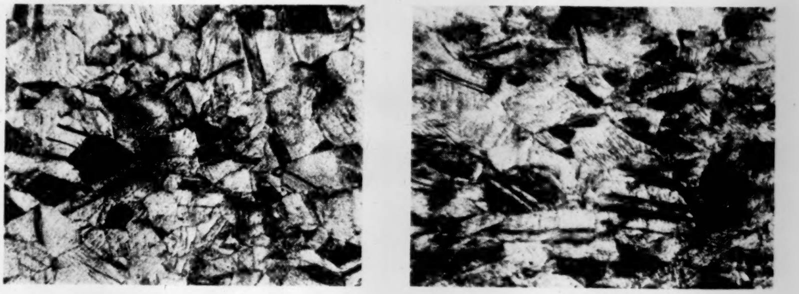
MICROSTRUCTURE OF .30 CALIBER CARTRIDGE BRASS.
Etched with Ammonia and Hydrogen Peroxide.
Magnification, ×75.



Brinell 118. Brinell 135.

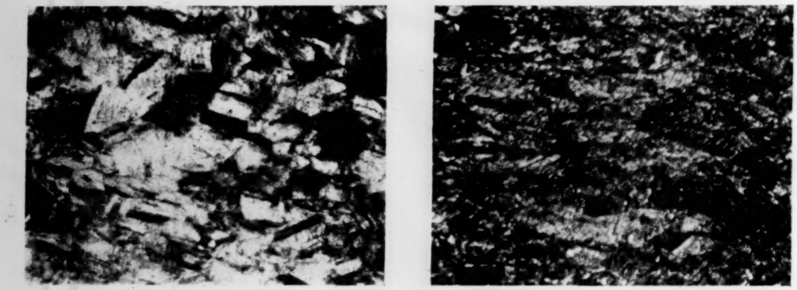


Brinell 128. Brinell 143.



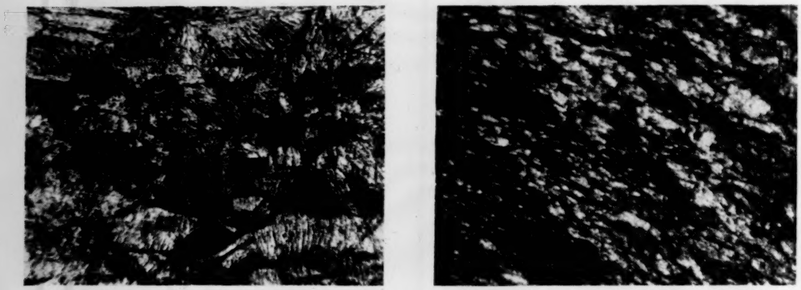
Brinell 131. Brinell 147.

MICROSTRUCTURE OF .30 CALIBER CARTRIDGE BRASS.
Etched with Ammonia and Hydrogen Peroxide.
Magnification, ×75.



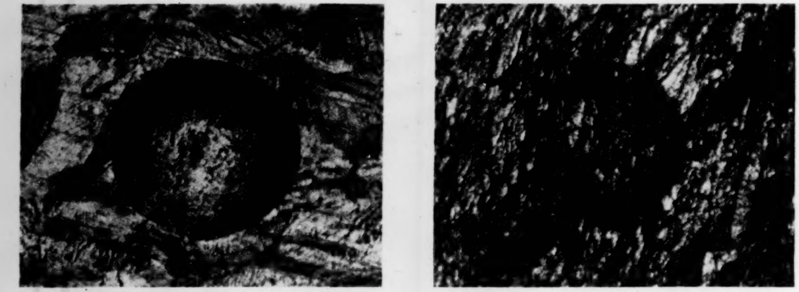
Brinell 155.

Brinell 190.



Brinell 159.

Brinell 190.



Brinell 170.

Brinell 200.

MICROSTRUCTURE OF .30 CALIBER CARTRIDGE BRASS.
Etched with Ammonia and Hydrogen Peroxide.
Magnification, ×75.

was taken, a small oil pipe has been added for flow of oil from below the piston to the needle valve, connected by a union, a convenience in case it is necessary to repair or clean the needle valve.

A photograph of three anvils used on our special work is shown in Fig. 7. The cone-shaped one can be used with flat top for flat sheet, or with top made cylindrical for curved sheet as when testing sections of pipe. The expanding anvil can be used for testing pipe without splitting, and the block anvil can be used for testing the cross-section of wall of thick walled small pipe. Other anvils can be devised for other special cases, the main point being to insure that the anvil is in perfect contact with the under side of the sheet immediately under the ball impression and that the specimen is firmly held. No effect of the impression should show through on the under side of the sheet tested.

The relationship of Brinell hardness to microstructure can best be shown by actual micrographs corresponding to various hardnesses. Both grain size and occurrence of work lines must be considered in the comparisons. Our work has shown that there is no direct relationship between hardness and grain size in annealed brass. It is possible to secure brass of say Brinell 100 and with relatively fine or relatively coarse grain.

Eighteen micrographs are shown giving typical structures of brass of various hardness from about 70 to fully work-hardened brass of 200. As stated above other samples may show considerably different grain size for the various stages of hardness from those shown here.

It is believed that it is possible to combine the Brinell test with microscopic examination so as to give a reliable check on manufacturing operations in working and annealing brass and on the quality of finished brass articles.

It is desired to acknowledge with thanks the assistance given by Capt. C. Upthegrove, now on the faculty at the University of Michigan, in the preparation of this paper. Captain Upthegrove was closely associated with the development and application of these Brinell machines and his work has been freely drawn upon.

APPARATUS FOR DETERMINATION OF BREAKING POINT OF PITCHES.

By H. E. Lloyd and P. P. Sharples.

SUMMARY.

A method of determining the breaking point, based on the English test of breaking a rod of pitch, has been developed.

The apparatus consists of a metal hinge on which is placed a bar of pitch cast in a mold. Apparatus is provided for bending the hinge, submerged in cold water, at a constant rate until a fracture results in the bar of pitch. The temperature of the water is then raised and the process repeated until no fracture occurs. Tests may be made at the higher temperatures first if preferred, cooling the water for successive tests until fracture occurs.

The temperature is reported at which the pitch last shows no break and also the temperature at which fracture takes place. The two temperatures are obtainable within 1° C., and are capable of duplication by different observers.

Tables are given showing the results of tests on various pitches and by different operators on the same pitch. The paper is accompanied by photographs and a diagram showing the construction of the apparatus.

APPARATUS FOR DETERMINATION OF BREAKING POINT OF PITCHES.

BY H. E. LLOYD AND P. P. SHARPLES.

The published method for determining the breaking point of pitches used in the Research Laboratory of the Barrett Co. is to melt a small piece of pitch on a copper disk in a layer about $\frac{1}{32}$ in. thick. This disk is then placed in a porcelain dish and covered with water of about 10-12° C. above the breaking point of the pitch. The temperature of the water is reduced 1° C. per minute and tested from time to time by inserting a small thin knife blade below the pitch and turning slightly until a point is reached at which the pitch snaps.[1] This method has a large personal equation and is not desirable for record work or laboratory comparisons.

The genesis of the new method came from the refinement of the method used in England of breaking by hand a rod formed of pitch.

FIRST FORM OF APPARATUS.

In the first form of apparatus, a hinged trough was constructed in which a bar of pitch could be bent upward under a fixed rod or fulcrum. This hinge was made of brass, and was $12\frac{3}{4}$ in. long and $1\frac{1}{16}$ in. in inside width. Two plates were attached to one section of the hinge with screws. The other section carried drilled hinge lugs fitting into the plates of the first section. The hinge could be attached to a heavy iron base by passing the pin or fulcrum through the supports and the drilled lugs. One support carried a wing with a hole in it so that the pin could be secured firmly.

Two branch chains attached to the outer arms of the hinge were joined and passed over two pulleys and a weight of 3.6 kg. was attached to the end of the chain. The plate to which the hinge was attached was placed in a large aquarium jar on a circular iron stand. Pressure was applied by releasing the weight gradually so as to give a slow steady pull on the chains.

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[1] S. R. Church, *Journal of Industrial and Engineering Chemistry*, Vol. III, No. 4, (1911).

To make the test, the pitch was first carefully melted to avoid volatilization as far as possible and poured into the mold, previously greased with a thin film of vaseline. After cooling for 10 or 15 minutes, the bar was removed and placed in the hinge, which was then attached to its supports by passing the pin over its top into position. The chains were attached and water poured into the bath. A temperature somewhat above that estimated as the breaking point for the pitch was maintained for at least 15 minutes and then a trial made by attaching the weight and gradually allowing its force to close the hinge to an angle of 90 deg., or until a break occurred. If not broken, another bar was placed on the hinge, the temperature of the bath lowered 10° C., and the test repeated. In this way, working between limits and gradually narrowing them, a point was reached at

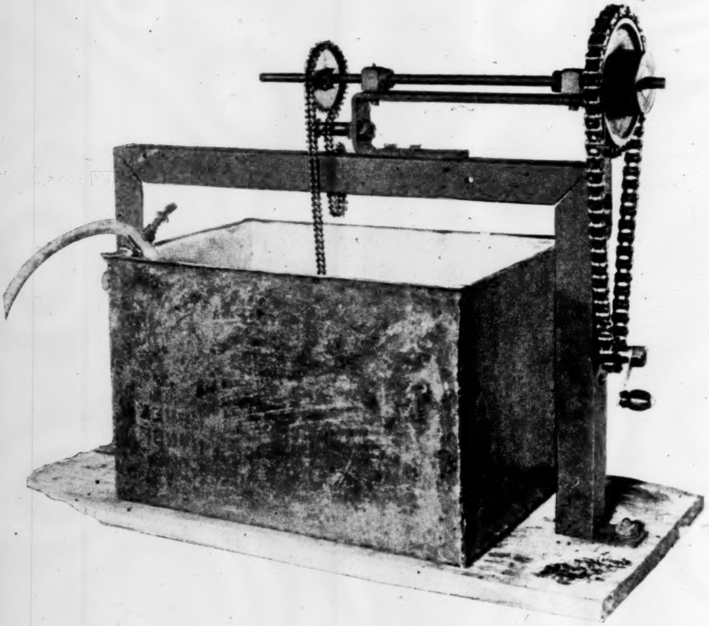

FIG. 1.—First Form of Apparatus.

which a change of usually 1° C. would show a break or no break. This was called the "breaking point."

Even with this rather crude method of applying the bending force check results were obtained. By adding a gear arrangement whereby the hinge could be closed at a uniform rate, the apparatus was much improved. The gear ratio adopted was five to one; in testing, the handle on the small gear was turned at the rate of one-half turn per second. Fig. 1 is a reproduction of this earlier instrument as thus modified.

Very good results were obtained with this apparatus, but it was found to be inconvenient in removing the hinge from the bath.

PRESENT FORM OF APPARATUS.

The apparatus as finally designed is illustrated in Figs. 2 and 3. It consists essentially of a cast-iron base supporting a rod in a standard which carries shaft, gears and suspended hinge. This rod can be raised and lowered inside the standard casing and is secured by set screws in any position desired. After making the test, the hinge may readily be raised from the water bath and the pitch bar inspected. All parts which come in contact with the water are made of brass. Following is the procedure in making the test:

Method of Making Test.—The pitch to be tested is carefully melted and poured into a mold as previously described, and allowed to cool until hard. In the case of the softer pitches, the semi-solid material enclosed in the mold can be placed in a basin of cold water for hardening. The pitch bar thus formed is 12 by 1 by $\frac{1}{4}$ in. It is placed in the hinge, which has been raised above the surface of the water in the bath. The hinge pin is inserted and locked, the chains are attached to the ends of the hinge, and the whole is lowered into the water, where it should remain for at least 15 minutes before testing. The temperature of the water should not vary more than $\frac{1}{2}$° C. during this time. Ice may be added to the water for cooling purposes if the water is agitated by a jet of air or stirrer. At low temperatures, a brine solution may be used.

After the bar of pitch has attained the temperature of the water, it is bent upward under the pin through an angle of 180

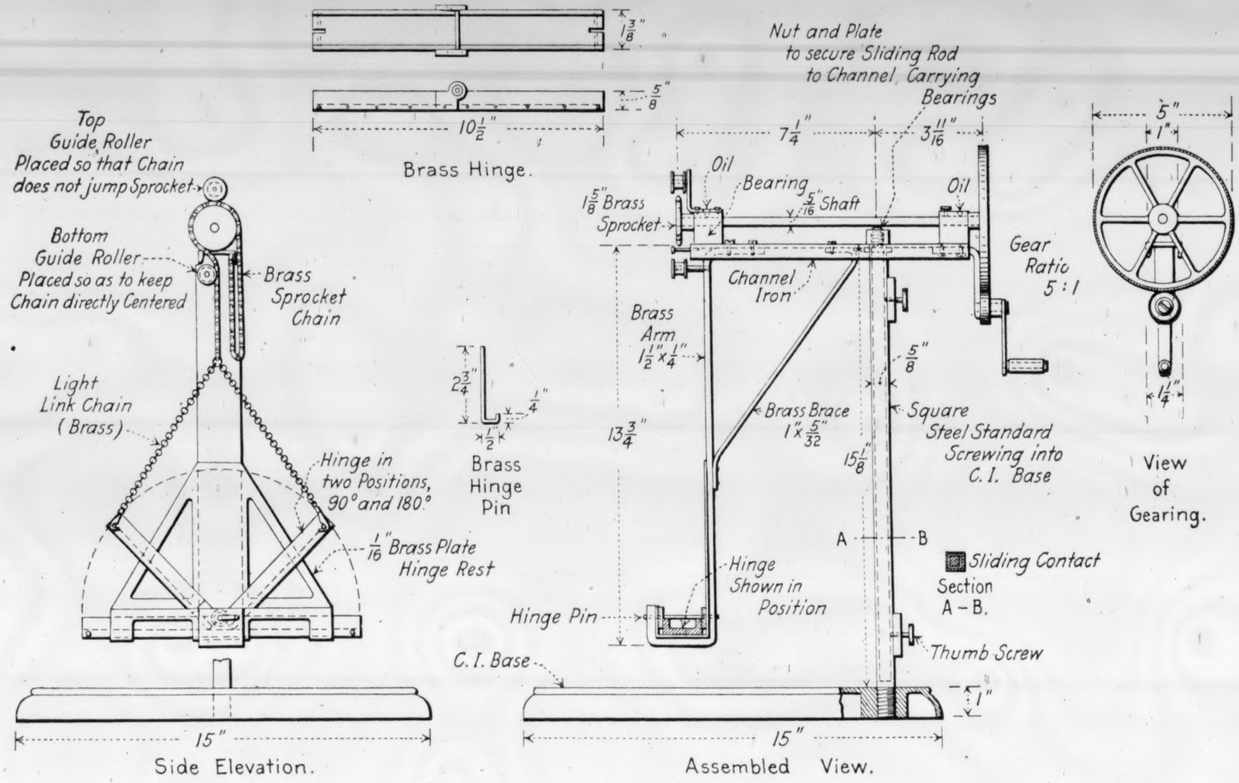
Brass Hinge.
1 3/8"
5/8"
10 1/2"
Top Guide Roller Placed so that Chain does not jump Sprocket
Bottom Guide Roller Placed so as to keep Chain directly Centered
Brass Sprocket Chain
Light Link Chain (Brass)
Hinge in two Positions, 90° and 180°
1/16" Brass Plate Hinge Rest
2 3/4"
1/4"
1/2"
Brass Hinge Pin
15"
Side Elevation.
Nut and Plate to secure Sliding Rod to Channel, Carrying Bearings
7 1/4"
3 11/16"
Oil
Bearing
5/16" Shaft
1 5/8" Brass Sprocket
Oil
Gear Ratio 5 : 1
Channel Iron
Brass Arm 1 1/2" x 1/4"
5/8"
13 3/4"
Brass Brace 1" x 5/32"
Square Steel Standard Screwing into C. I. Base
15 1/8"
A
B
Hinge Shown in Position
Sliding Contact
Section A – B.
Hinge Pin
Thumb Screw
C. I. Base
1"
15"
Assembled View.
5"
1"
1 1/4"
View of Gearing.

FIG. 2.—Details of Final Form of Apparatus.

deg. by turning the handle on the lower sprocket wheel at the rate of one turn in two seconds. The carrier is raised from the water after the test and the bar examined. By narrowing the temperature limits a point is finally reached where a variation

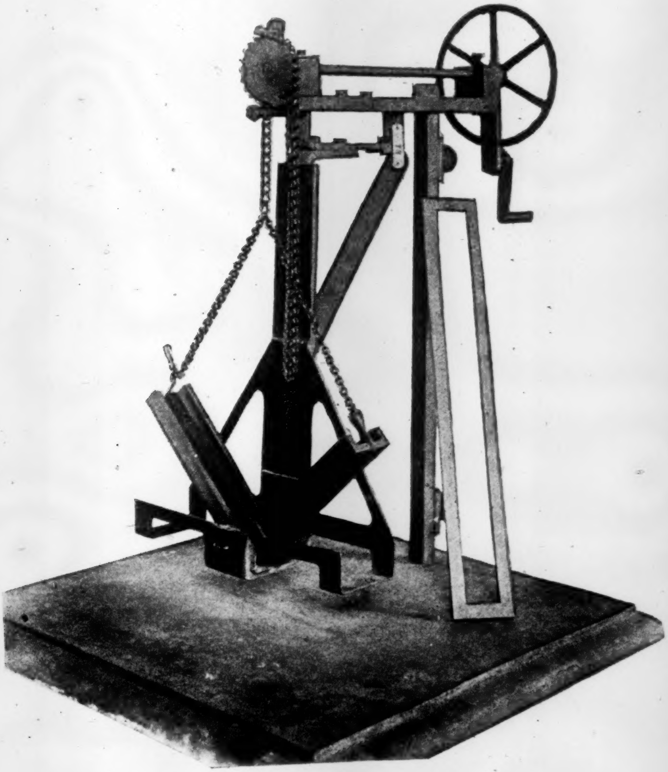

FIG. 3.—Final Form of Apparatus.

of 1° C. will show a break or no break. This is the "breaking point" and is recorded in the following manner:

Break at	10° C.
No break at	11° C.

That is, a specimen at 11° C., for example, will bend through an angle of 180 deg. without breaking, whereas a specimen at

10° C. will break in two pieces when bent through the same angle. Occasionally a pitch is found that will crack when bent through 180 deg. but will not break. Cracks are disregarded in recording the tests and the breaks only are recorded.

TABLE I.—BREAKING POINT TESTS OF SINGLE PITCH WITH DIFFERENT OPERATORS.

Melting Point (cube in water), deg. Cent.	Free Carbon, per cent.	Breaking Point, deg. Cent. Operators.				
		No. 1	No. 2	No. 3	No. 4	No. 5
51.5................	19.1	6–5	8–7 6–5 6–5 6–5	.....	8–7	6–5
60.5................	9.5	18–17	16–15 17–16 17–16	16–15 16–15	17–16	17–16
61..................	37.4	13–12	13–12	.....	.....	.....

For the preliminary tests, pieces of the original bar may safely be used. Comparative tests have also shown that bars 4 and 6 in. in length give the same results as bars 12 in. in length. Therefore, the original 12-in. bar may be cut into two or three pieces. The test may be hastened considerably by providing several molds, filling them all at the same time and immersing them in the water bath below the hinge where they will be kept at the desired temperatures.

TABLE II.—BREAKING POINTS OF VARIOUS PITCHES.

Melting Point (cube in water), deg. Cent.	Free Carbon, per cent.	Breaking Point, deg. Cent.
38................	7.0	−3–2
45.5..............	32.2	1–0
48................	3.0	5–4
57................	27.6	16–15
62................	27.5	21–20

SOME TEST RESULTS OBTAINED.

The breaking points of several pitches determined with this apparatus are given in Tables I and II. From Table I it is seen that the breaking points can be determined accurately and that each operator can check his own results and those of other operators very closely. Table II is a record of tests on a variety of pitches.

The method has been used in the Research Laboratory over a considerable period of time and has given satisfactory results. The apparatus could be measurably improved, however, by making it possible to observe the break in the pitch without raising the apparatus out of the water.

DISCUSSION.

Mr. Wilson. MR. J. J. WILSON.—The authors are to be commended for their investigations of a subject which has been somewhat neglected in the past. It is difficult to get a method for the brittle point test that will give concordant results in the hands of different operators.

There are two or three questions regarding the instrument which I would like to ask the authors. Is the instrument applicable to materials that have very low breaking points, say 25° C. below zero? Is it applicable to asphalts and mixtures of asphalt and pitch? We frequently find it necessary to test material of very low breaking points, and some specifications for pipe dips call for mixtures of asphalts and pitches.

Mr. Sharples. MR. P. P. SHARPLES.—There is absolutely no difficulty in using the apparatus for testing existing mixtures of asphalt and pitch. We have lately completed a long series of tests on pitch and asphalt combinations, and the apparatus has worked admirably. The testing of materials as low as 25° C. below zero would depend on getting a medium that would remain liquid at that low temperature. There is no difficulty in getting good results as low as 10° C. below zero with ice and salt, and mixtures of calcium chloride and ice should give much lower temperatures without difficulty.

Mr. Upham. MR. C. M. UPHAM.—I understood Mr. Sharples to say there was some trouble experienced in determining when the bar of pitch cracks. Has he tried suspending the trough at the center instead of the end, so that the crack would appear on the top rather than on the bottom?

Mr. Sharples. MR. SHARPLES.—We have not tried a type of apparatus that would enable us to inspect the fracture without removing the bar of pitch from the water, as it was easier in this development work to keep the type constant. We fully realized, however, that it would be easier to work with a type of apparatus that would allow constant inspection of the bar and I see no mechanical difficulties in arranging the apparatus so as to bring the break on top in full view.

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